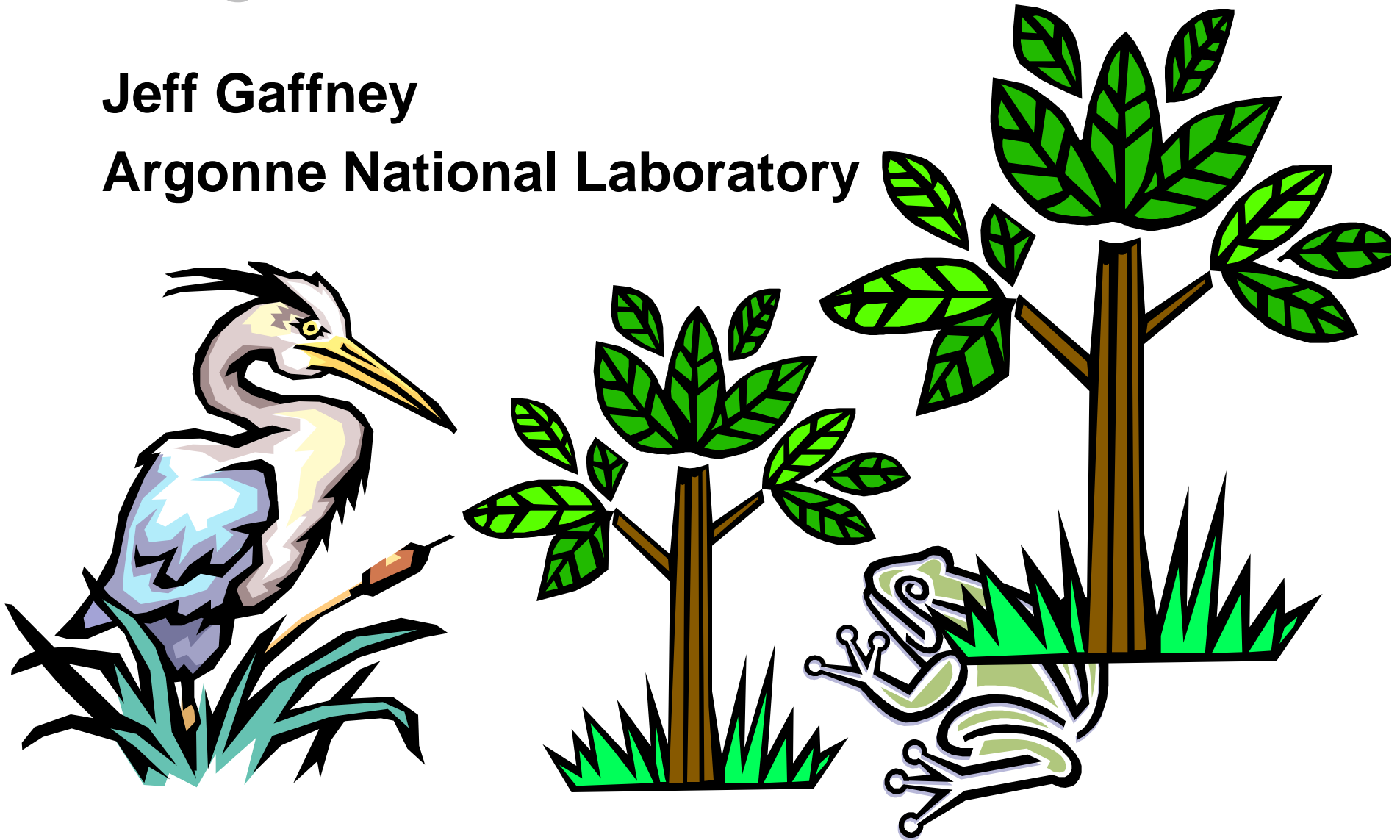


Ecology and Carbon Sequestration Program Overview

Jeff Gaffney

Argonne National Laboratory



DOE Consortium for Research on *Enhancing* Carbon Sequestration in Terrestrial Ecosystems

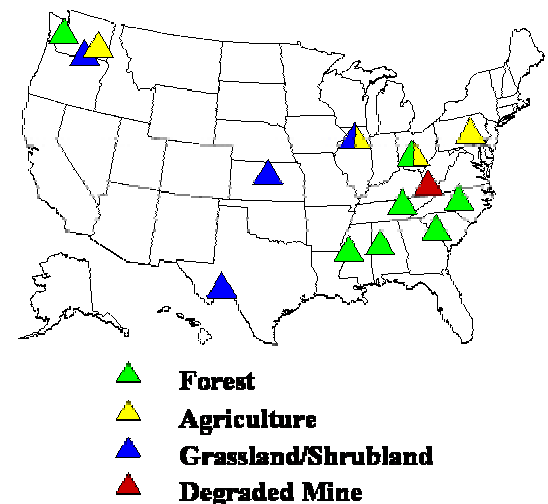


Introduction

Gary Jacobs

Oak Ridge National Laboratory

March 19, 2003



National Laboratories

- Argonne National Laboratory
- Oak Ridge National Laboratory
- Pacific Northwest National Laboratory

DOE

- National Energy Technology Laboratory

Universities

- Colorado State University
- University of California - Davis
- Cornell University
- North Carolina State University
- Ohio State University
- Rice University
- Texas A&M University
- University of Washington

Research Institutions

- Joanneum Inst for Energy Res, Austria
- USDA Center for Forested Wetlands Res, SC
- USDA Land Mgmt & Water Cons Unit, WA
- USDA Coshocton Watershed



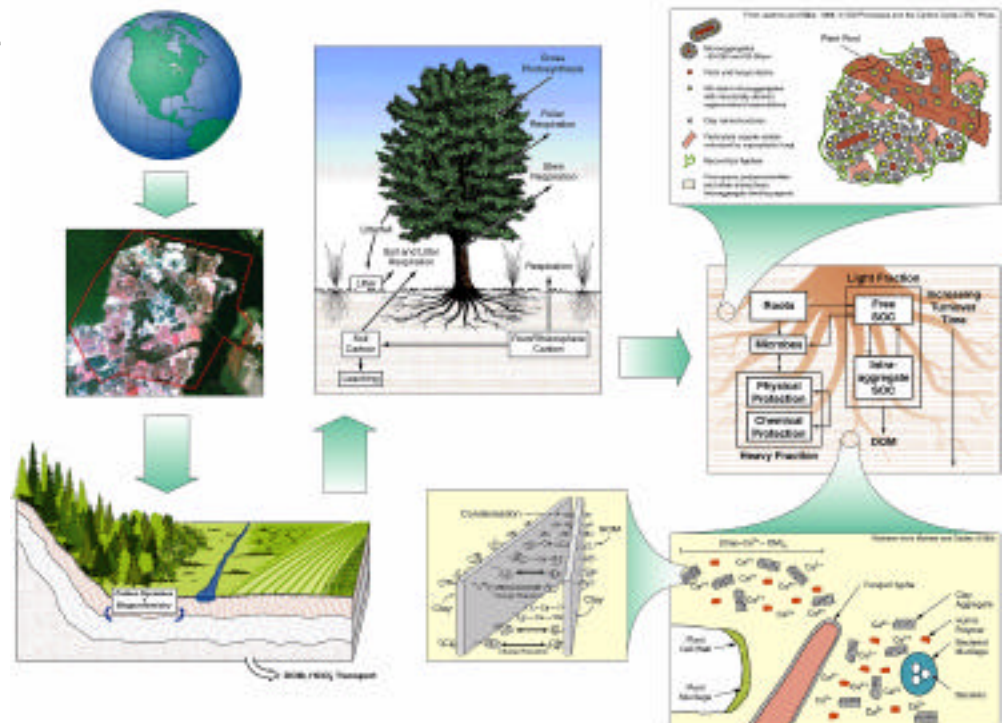
CSiTE Mission

Fundamental science supporting approaches for enhanced sequestration

Soil carbon focus within context of whole ecosystems

- 1 Discover how to alter carbon capture and sequestration mechanisms from molecular to landscape scales
- 2 Develop conceptual and simulation models for extrapolation across spatial and temporal scales
- 3 Advance science of assessing environmental and economic consequences of sequestration

Multi-scale & multi-disciplinary ORNL 98-0526/ISS

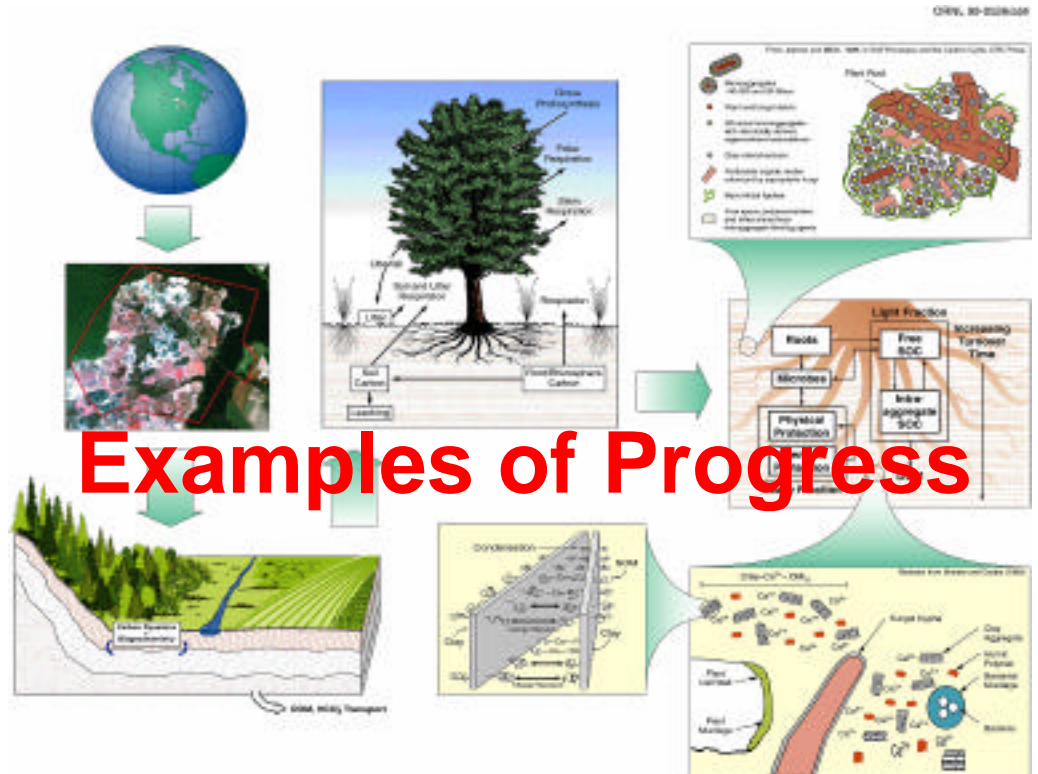


What's are some possible options to enhance carbon sequestration?

- ⇒ **Alter inputs (litter), root density, depth, chemistry**
 - Manage vegetation, alter cultivars
 - Fertilization, moisture, etc.

- ⇒ **Shift decomposition rates and products**
 - Shift structure and function of microbial communities
 - Modify chemistry

- ⇒ **Optimize physicochemical conditions**
 - Physical/chemical protection
 - Humification redox reactions
 - Promote deeper transport of C

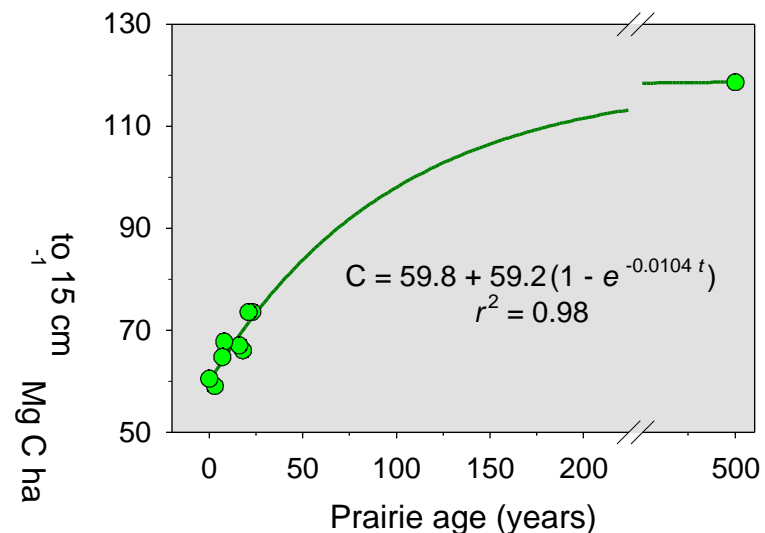
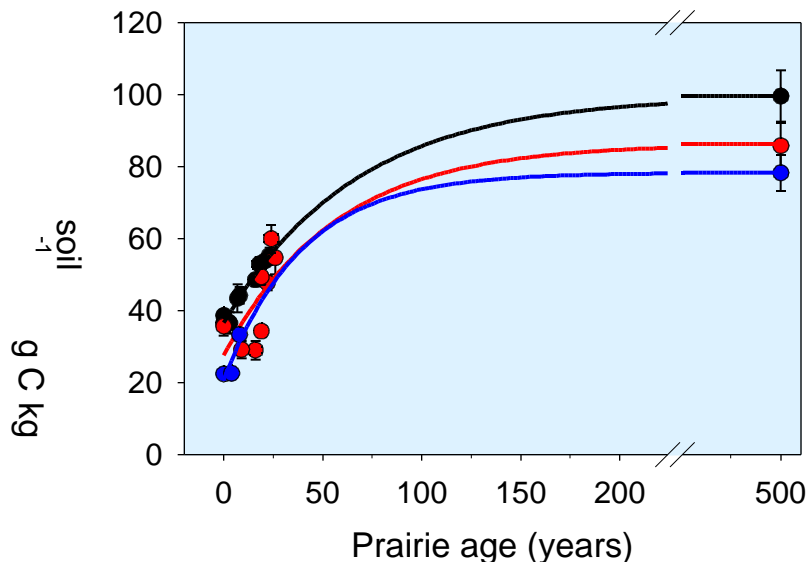


Selected Accomplishments

- ① Elucidation of controls on rates and limits of accumulation of soil organic C
- ① Fractionation methods leading to new insights on soil organic carbon capture and longevity
- ① Emerging manipulation concepts
- ① Microbial microarray technology for exploring soil carbon processes
- ② Advances in modeling tools
- ③ Model analysis of full CO₂ and greenhouse gas accounting
- ③ Analyzing economic implications

Elucidation of controls on rates & limits of accumulation of soil organic carbon

- ⇒ Inputs
- ⇒ Rates & Limits
- ⇒ Moisture
- ⇒ Nitrogen
- ⇒ Microbial processes

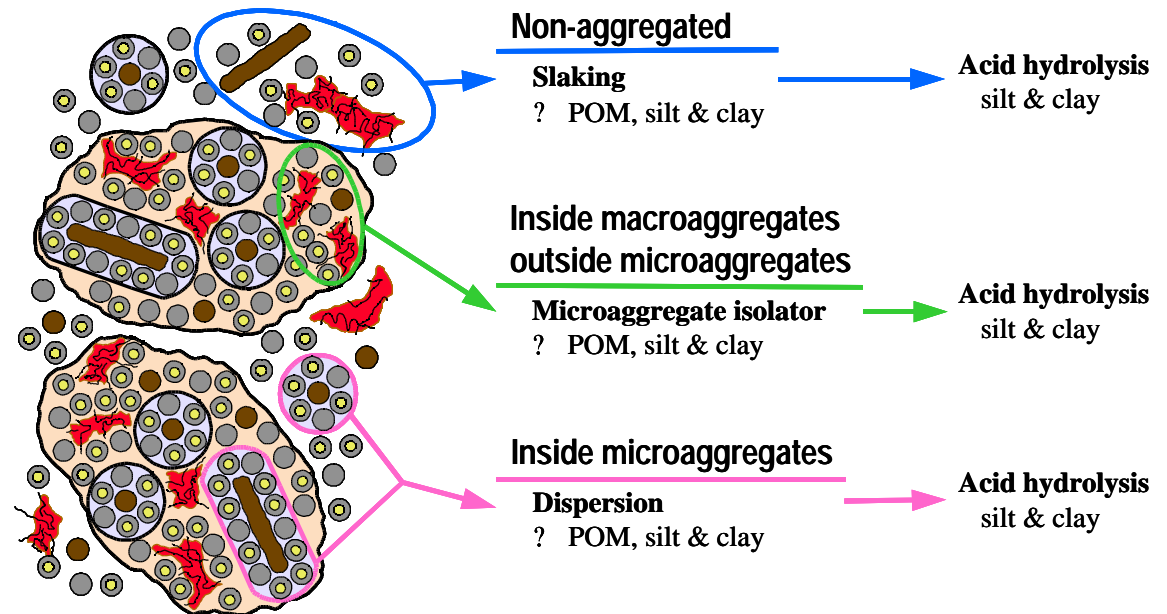


Fractionation methods leading to new insights on soil organic carbon capture and longevity

⇒ Soil organic matter is heterogeneous

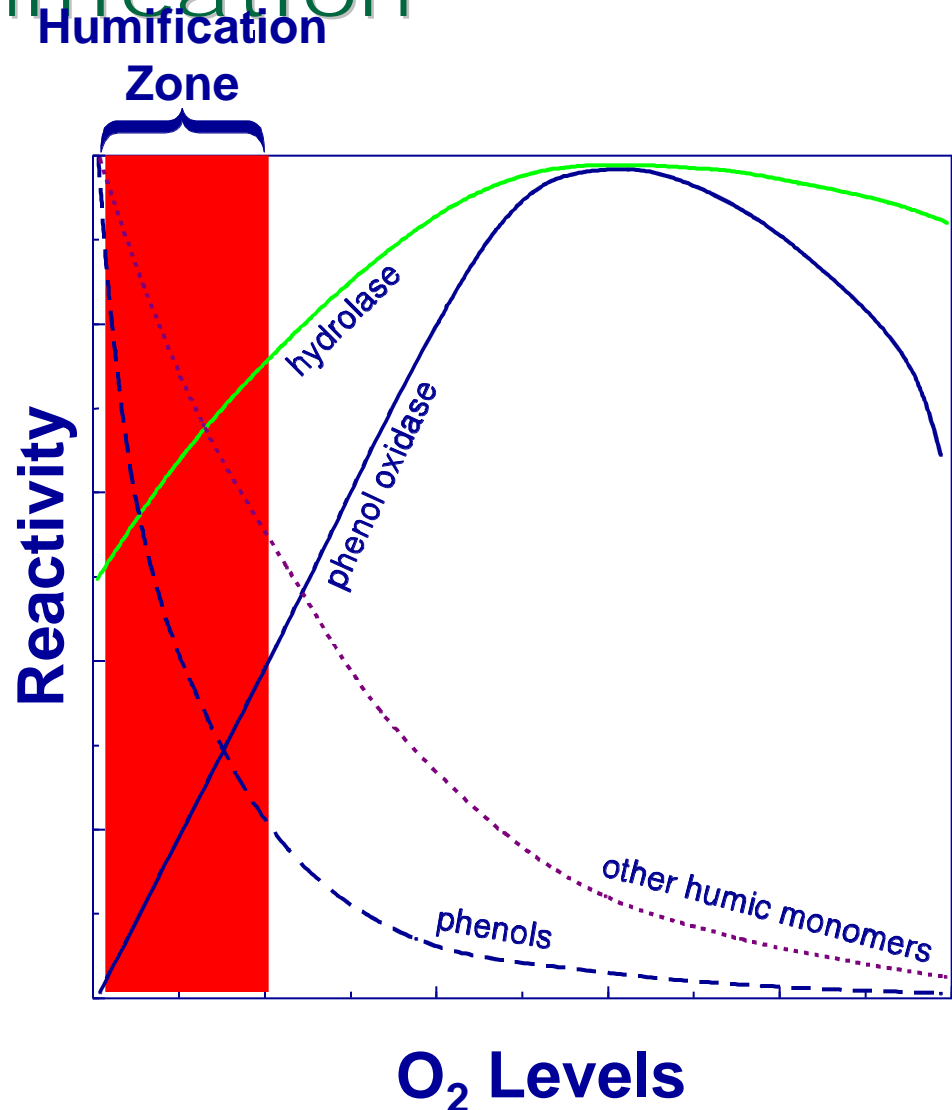
- Various physically protected forms
- Stages of chemical transformation
- Microsites with varying environmental conditions

⇒ Understanding processes that control C capture and longevity



Emerging manipulation concepts: Controls on humification

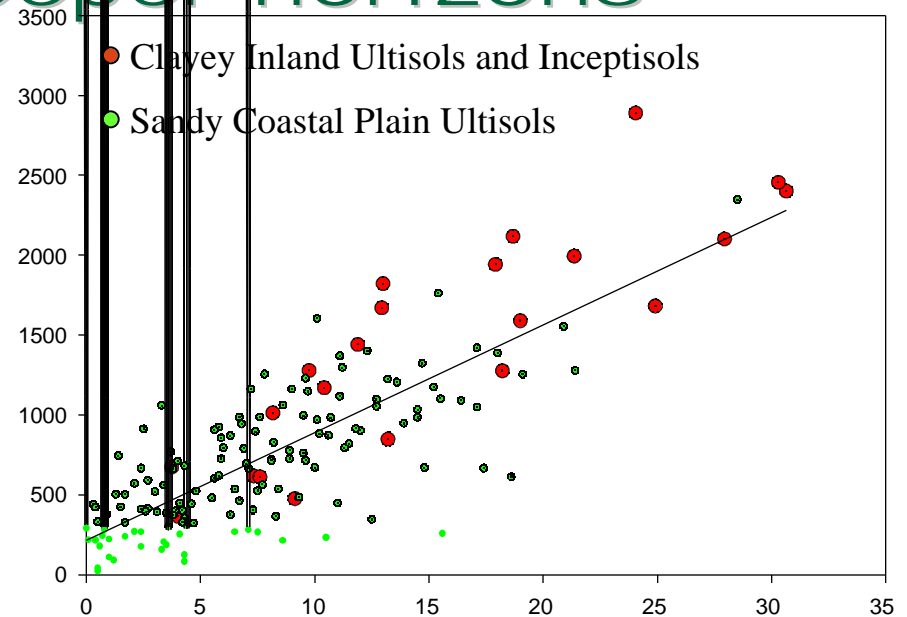
- ⇒ **Redox conditions**
 - Wetting/drying cycles
- ⇒ **Fe/Mn oxide content**
 - Fertilization
- ⇒ **Enzyme activities**
 - High-phenolic cropping, green manures, fungal/bacterial ratios



Emerging manipulation concepts:

Mobilization to deeper horizons

- ⇒ **Enhance hydrolysis of active organic C pools**
- ⇒ **Conversion to passive organic C pools**
- ⇒ **Amendments that promote deeper transport of C**
- ⇒ **Approach**
 - **Regional soils**
 - **Lab-scale studies**
 - **Field-scale manipulation**



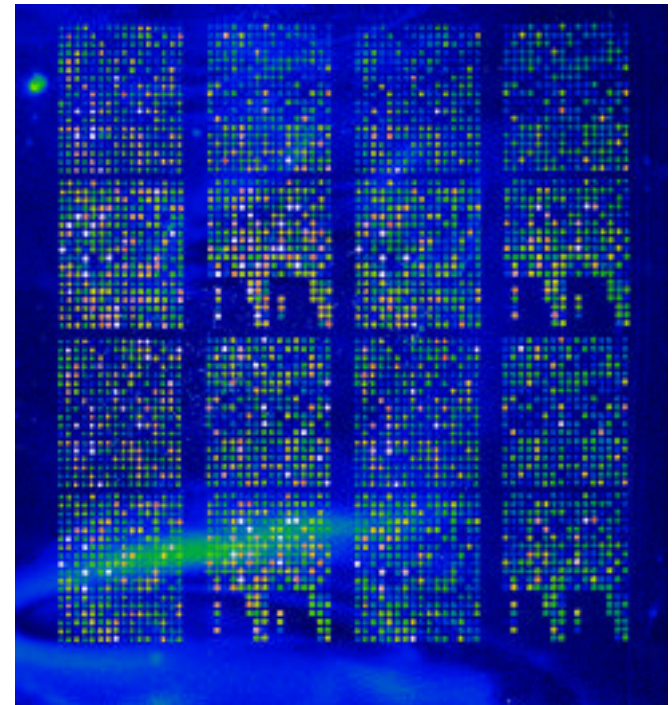
Microbial microarray technology for exploring soil carbon processes

Functional Gene Arrays allow insights into microbial
processes, community structure, and activities

6,698 gene probes from 30 organisms

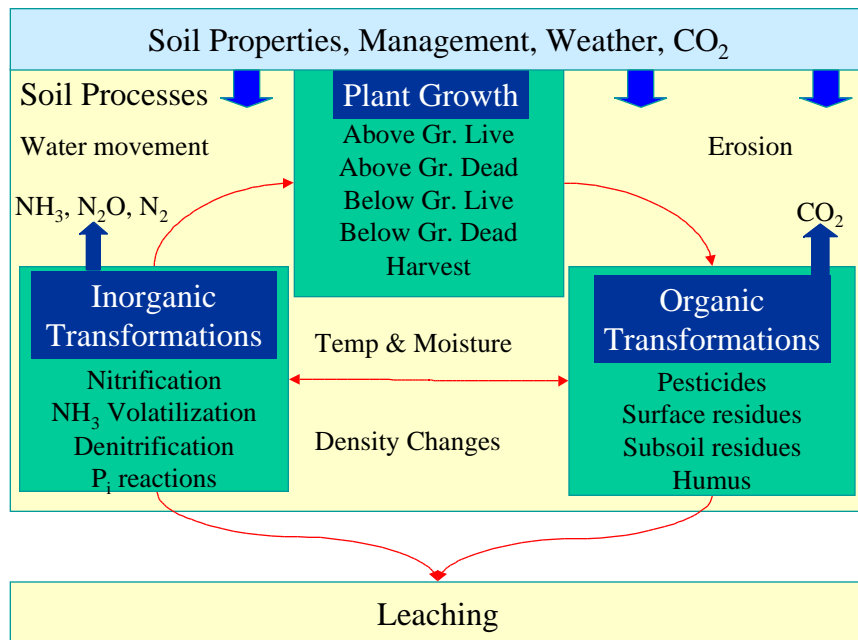
- **Nitrogen cycling: 1,882**
- **Sulfate reduction: 1,050**
- **Carbon cycling: 1,810**
- **Phosphorus utilization: 156**
- **Organic degradation: 1607**
- **Metal resistance and oxidation: 193**

**Preliminary results: Sample from
reclaimed mined lands
(NETL Project, Palumbo & Amonette)**



Advances in Modeling Tools: Improving process models and extrapolations

EPIC Model



- ⇒ Data are used to improve applicability of the model for spatial and temporal extrapolation
- ⇒ Combined with regional databases model can extend observations over conditions not directly measured
- ⇒ EPIC model also handles management and erosion

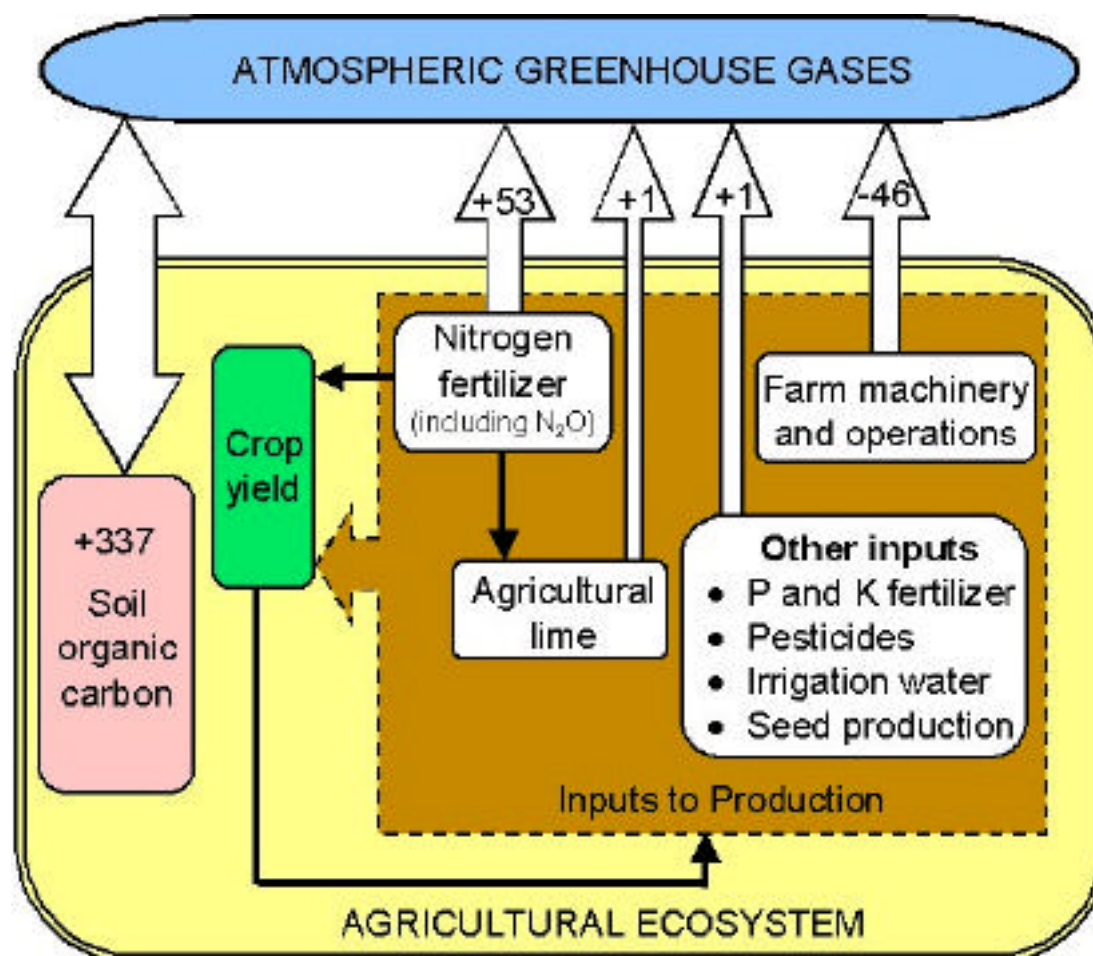
Model analysis of full CO₂ and greenhouse gas accounting

⇒ Agriculture

- Tillage
- Fuel
- Fertilizer/pesticides
- Lime, seeds
- N₂O, CH₄

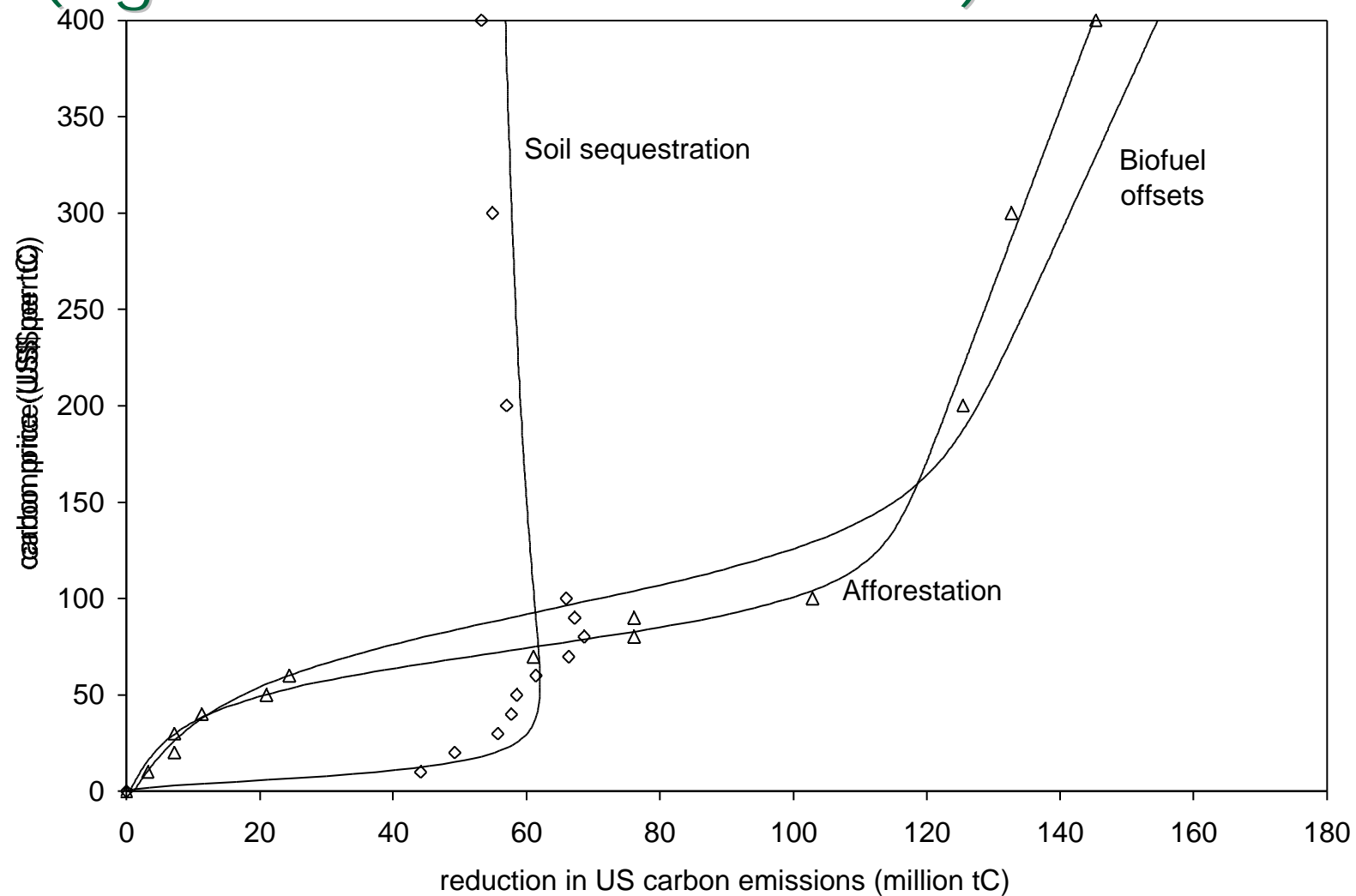
⇒ Forest harvest

- Forest growth, age
- Harvest operations
- Fate of wood products



West, T.O. and G. Marland. 2002. Environ. Pollution 116:437-442.

Analyzing economic implications (Agricultural Sector Model)



McCarl, B.A. and Schneider, U.A. (2001). *Science* **294**, 2481-2482.

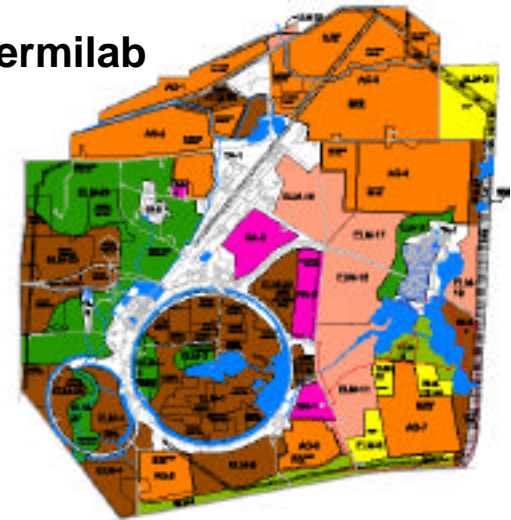


What you will hear today:

Multi-scale & Multi-disciplinary studies

- ⇒ **Discovery of options**
 - Understanding mechanisms to identify manipulation strategies (Fermilab)
- ⇒ **Tools for extrapolation**
 - Improve process models and landscape-scale simulations (Coshocton & Fermilab)
- ⇒ **Integrative Regional Study**
- ⇒ **Summary & Future Directions**

Fermilab



North Appalachian
Experimental Watershed
(Coshocton, OH)





Conversion of Croplands to Grassland: Understanding carbon sequestration dynamics, potentials, and mechanisms at multiple scales

Julie Jastrow

Argonne National Laboratory

**(with R. Matamala, M. Miller, V. Allison, ANL;
V. Bailey, H. Bolton, F. Brockman, J. Amonette, PNNL;
J. Smith, USDA-ARS; J. Six, UC Davis; C. Garten, ORNL)**

March 19, 2003



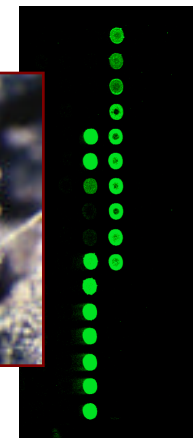
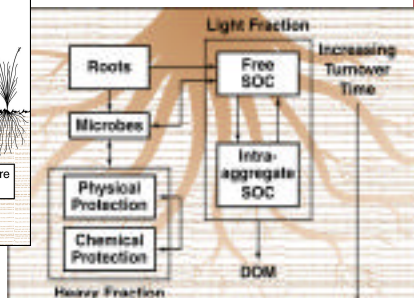
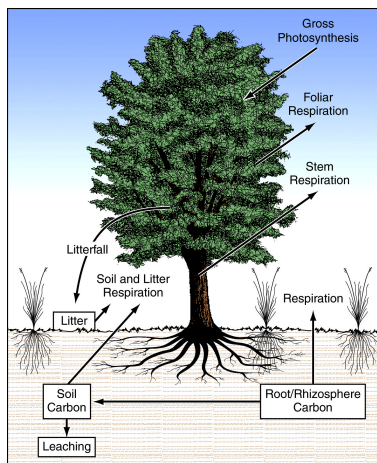
DOE National Environmental Research Park at Fermilab: Research site of opportunity

- ⇒ **Row-crop agriculture for ~150 y**
- ⇒ **Chronosequence of prairie restorations initiated in 1975**
- ⇒ **Prairie remnants**
- ⇒ **Fields converted to Eurasian pasture grasses c.1971**
- ⇒ **Woodlands**
- ⇒ **Wetlands**



Multi-scale/multi-disciplinary studies at Fermilab

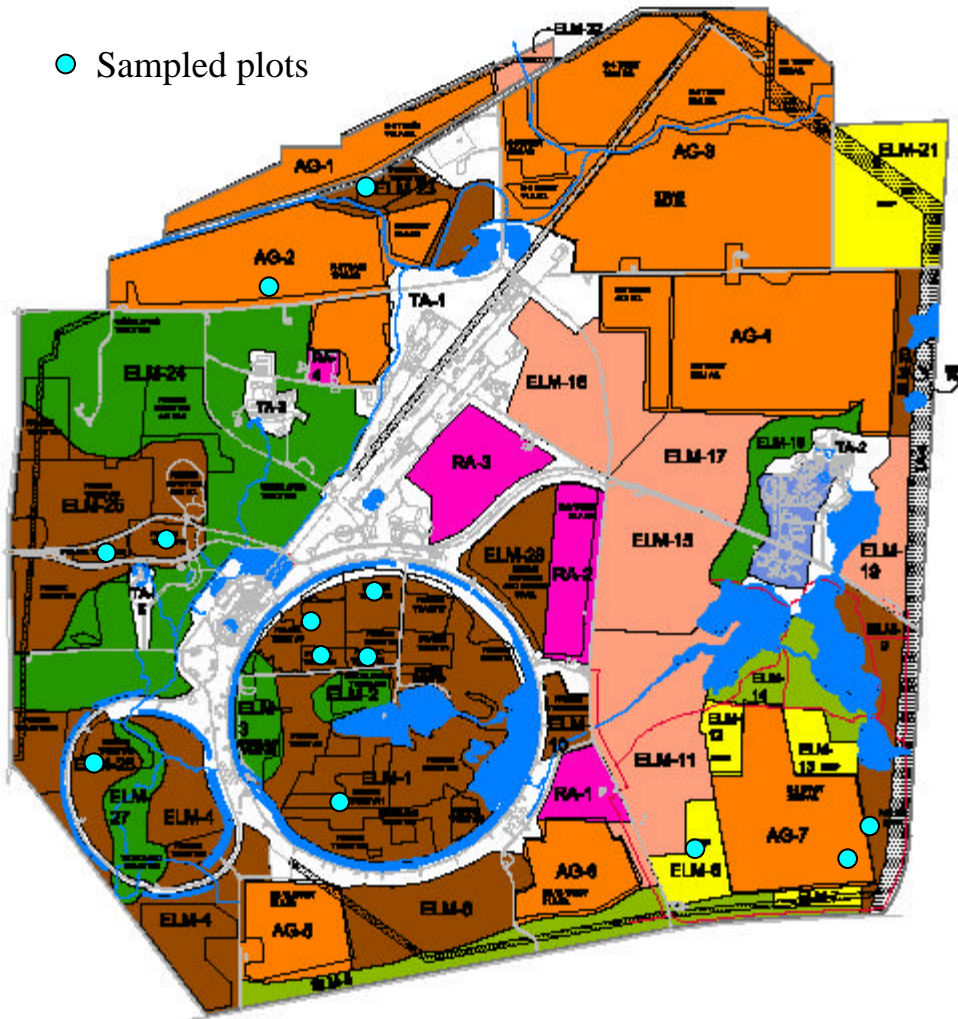
- ⇒ **Accrual of ecosystem C and N stocks**
- ⇒ **Nitrogen controls on C accumulation**
- ⇒ **Mechanisms controlling soil C stabilization**
- ⇒ **Microbial biomass, diversity, function and activity**
- ⇒ **Interfacial and molecular controls on humification**
- ⇒ **Model parameterization and validation**



nirS

Fermilab chronosequence studies

● Sampled plots



⇒ Three soil types

- Wet mesic, Drummer silty clay loam
- Mesic, Wauconda silt loam
- Dry mesic, Barrington silt loam

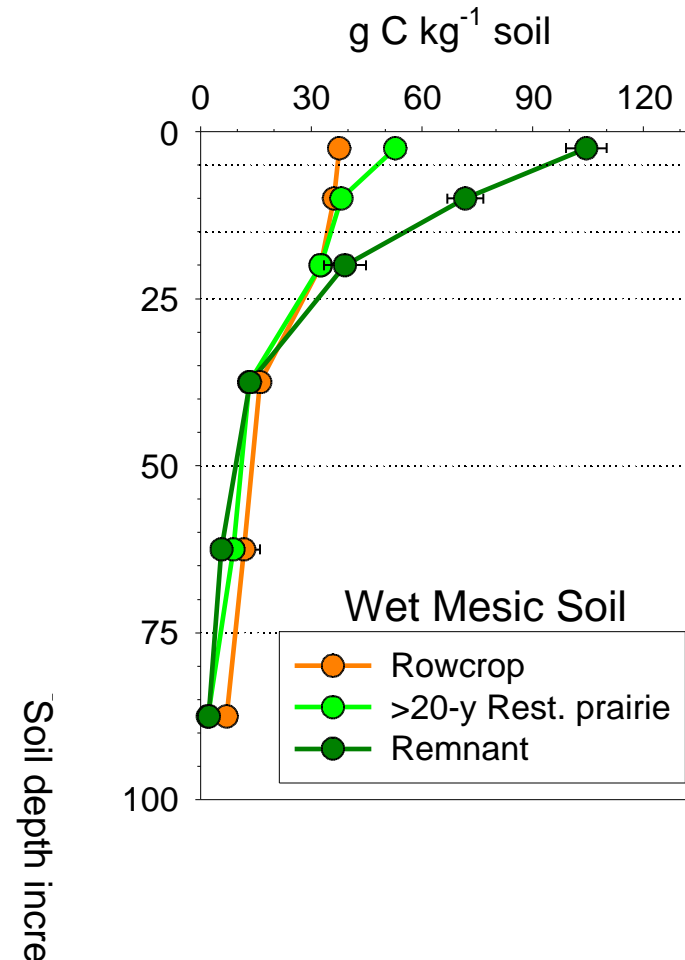
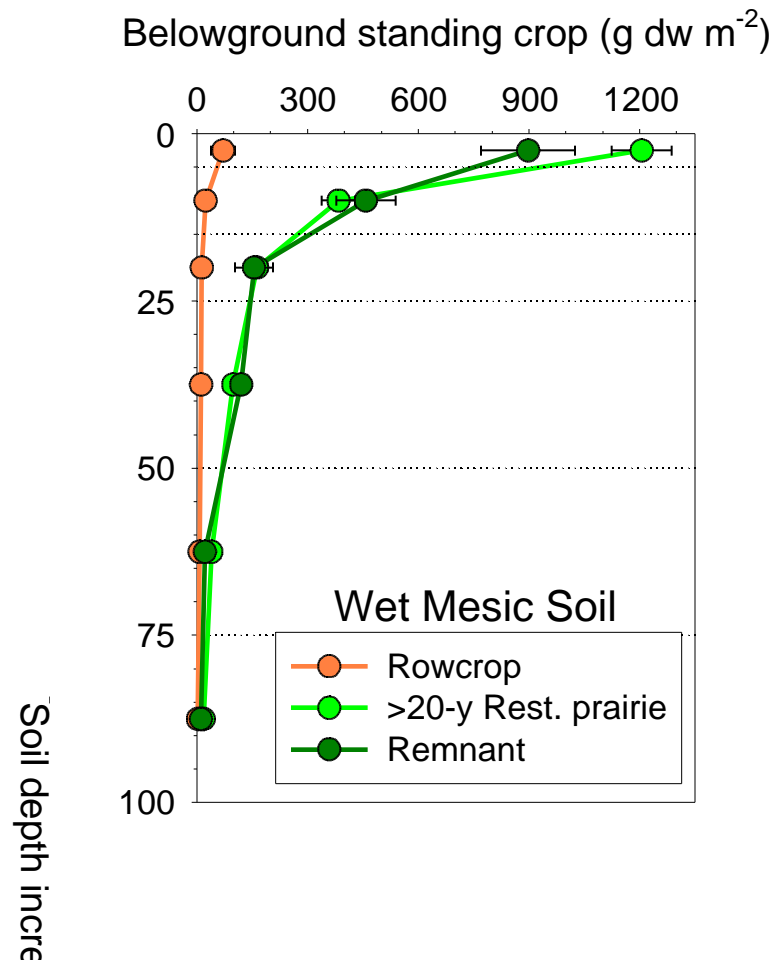
⇒ Chronosequence

- 2 Agricultural fields
- 9 Prairie restorations
- 1 Prairie remnant

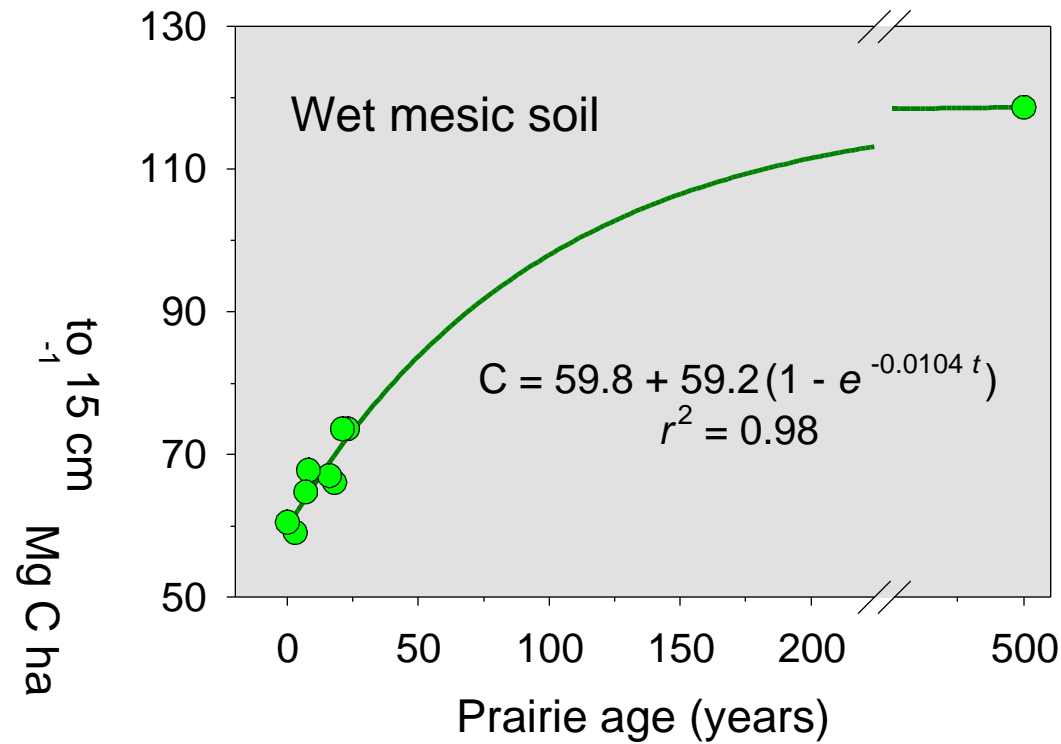
⇒ Sample above- and belowground (1-meter depth)

Depth distribution of inputs and soil C

- ⇒ Belowground biomass in older restored prairies equals or exceeds remnants
- ⇒ Root and rhizome inputs drive changes in soil C
- ⇒ Greatest soil C increases in surface 5-10 cm
- ⇒ Potential for long-term soil C accrual to 25-30 cm



Accrual of soil organic C sustained over 25 years



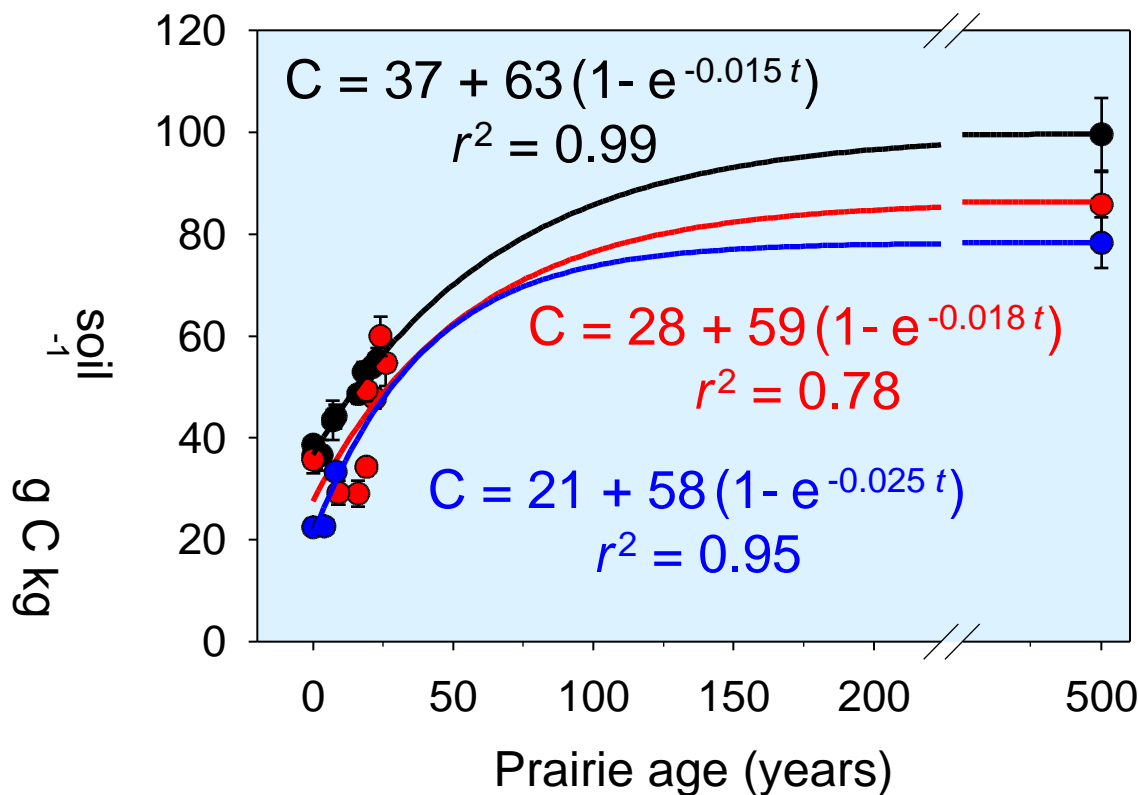
Based on equivalent soil mass
for 0-15 cm depth at time zero

Exponential model
predicts accrual of
0.54 Mg C ha⁻¹ y⁻¹
for 25 years in the
surface 15 cm

C_e	118.6 Mg ha ⁻¹
MRT	96 y
t_{50}	66 y

Effect of soil moisture/drainage conditions

- ⇒ Moisture affects equilibrium C for both disturbed and native
- ⇒ Initial rates of C accrual are similar
- ⇒ Time to equilibrium may vary

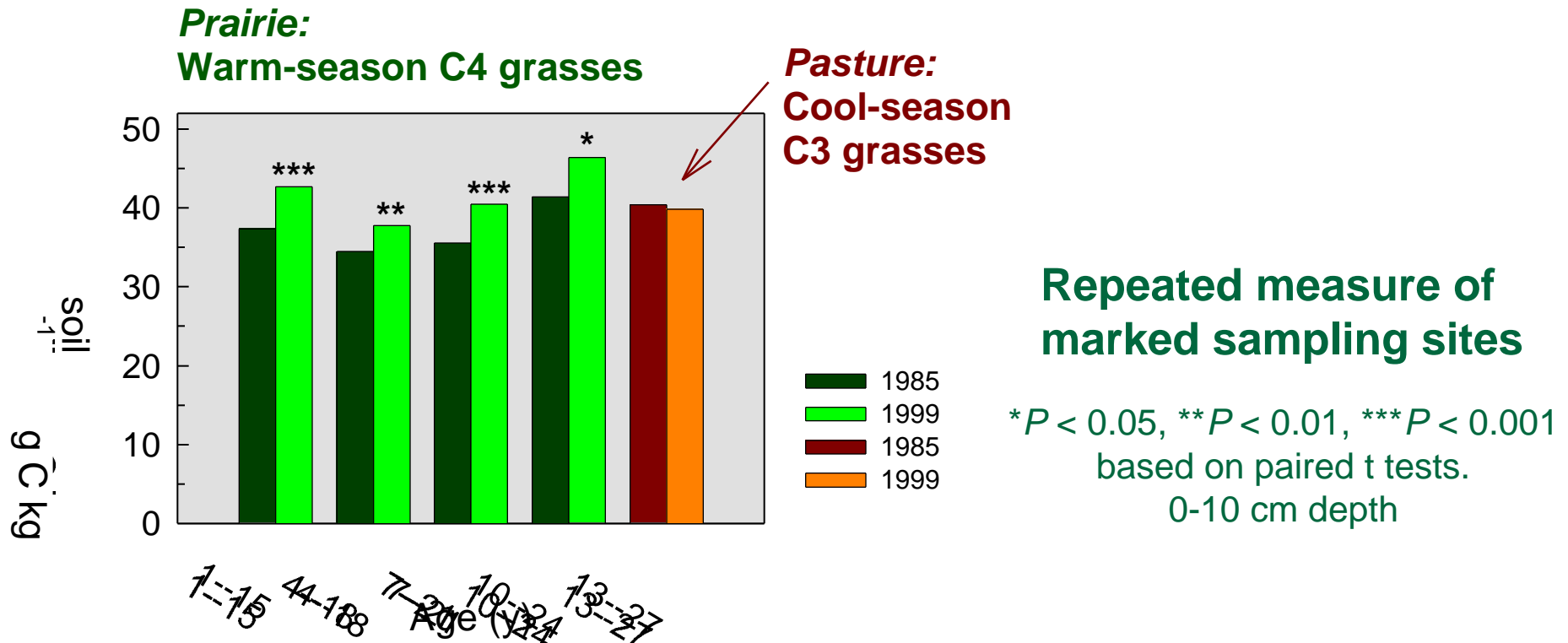


Protective capacity
of these soils
overcomes any
differences in inputs

% of C_e
accrued in 50 y

Wet mesic	53
Mesic	59
Dry mesic	71

Grassland type influences soil C accrual



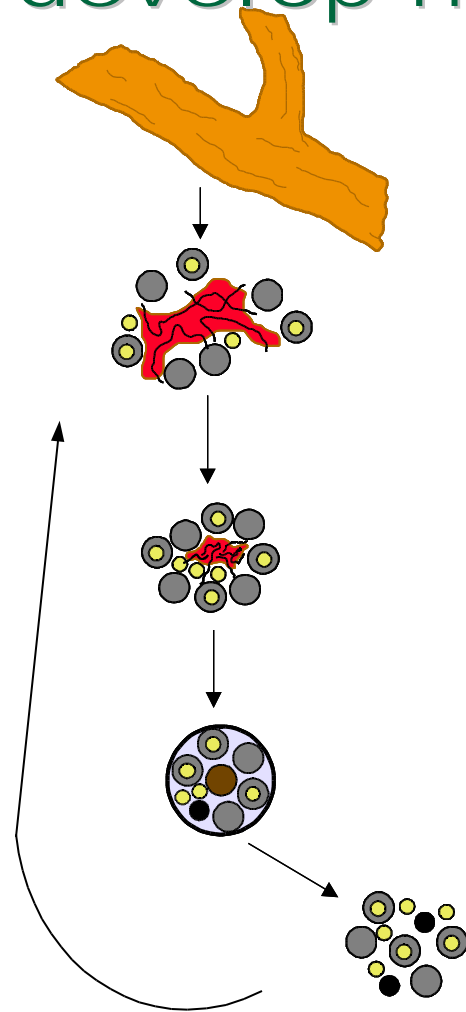
- ⇒ Prairie increments verify modeled rates
- ⇒ Pasture grasses at equilibrium by 13 years
 - Lower productivity (fertilizing might raise equilibrium)
 - Timing and quality of inputs affect decomposition

Changes in soil N cycling under restored prairie lead to accumulation of soil N

Site	Estimates based on ^{15}N pool dilution		
	Mineralization	NH_4 Consumption	Nitrification
	$\mu\text{g N g}^{-1} \text{ soil d}^{-1}$		
Row crop	22.2	17.5	14.7
8-y Prairie	11.6	9.5	0.1
22-y Prairie	4.3	9.7	0.3

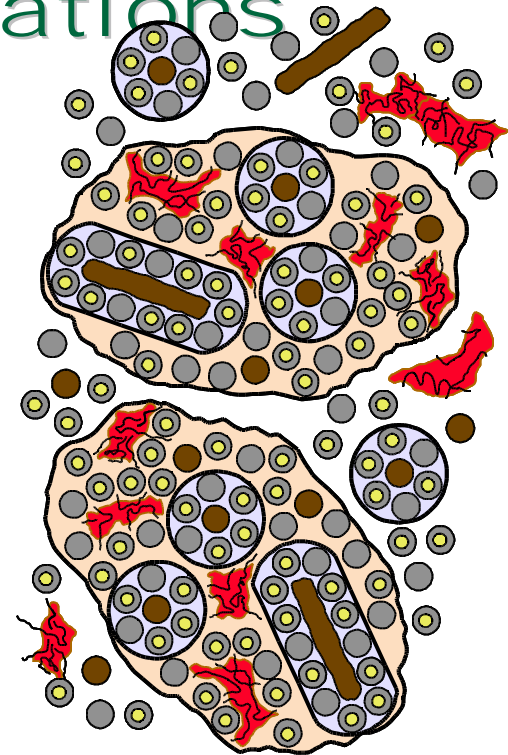
- ⇒ N cycling most rapid in the agricultural soil
- ⇒ Net N mineralization decreases with time in prairie
- ⇒ Increased N retention and tighter N cycling
- ⇒ N accrual sustains plant productivity and thus increases C storage








Conceptual models of soil C cycling and protection mechanisms used to develop new soil fractionations



Incorporation into microaggregates:

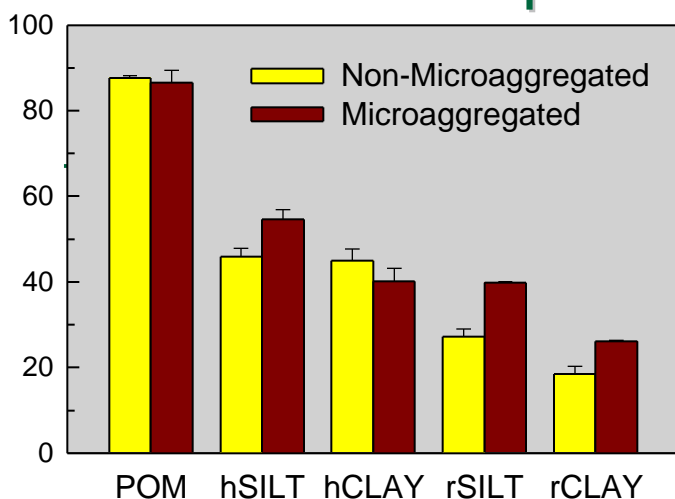
- ⇒ Physically protects organic inputs from decomposition
- ⇒ Enables organic matter to be humified or chemically protected by association with the mineral fraction



	Microaggregates ~ 50-250 μm		Plant and fungal debris
	Particulate organic matter colonized by saprophytic fungi		Fungal or microbial metabolites
	Silt-sized aggregates with microbially derived organomineral associations		Biochemically recalcitrant organic matter
			Clay microstructures

Mechanistic-based soil fractionations and stable isotopic tracers provide new

insights
into C capture and
storage
Microaggregates facilitate creation
of organomineral associations
(more new C in microaggregate-
associated silt and clay)

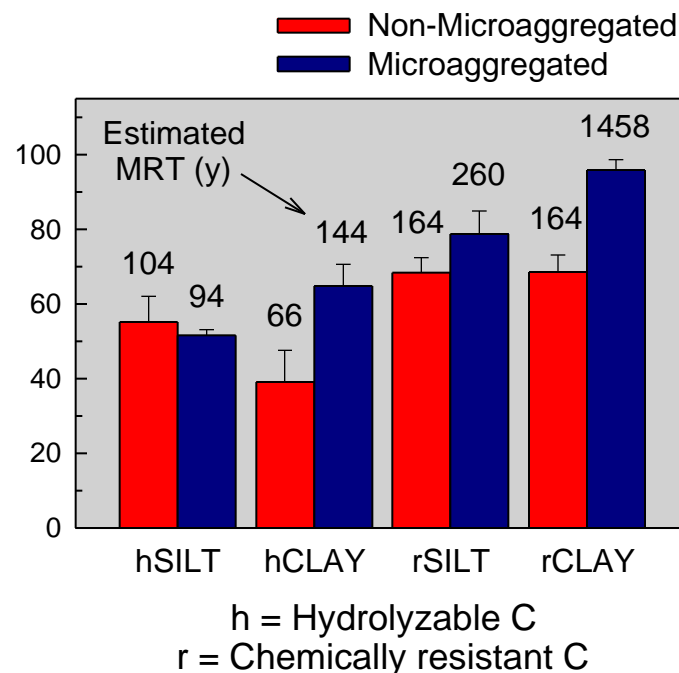


h = Hydrolyzable C
r = Chemically resistant C

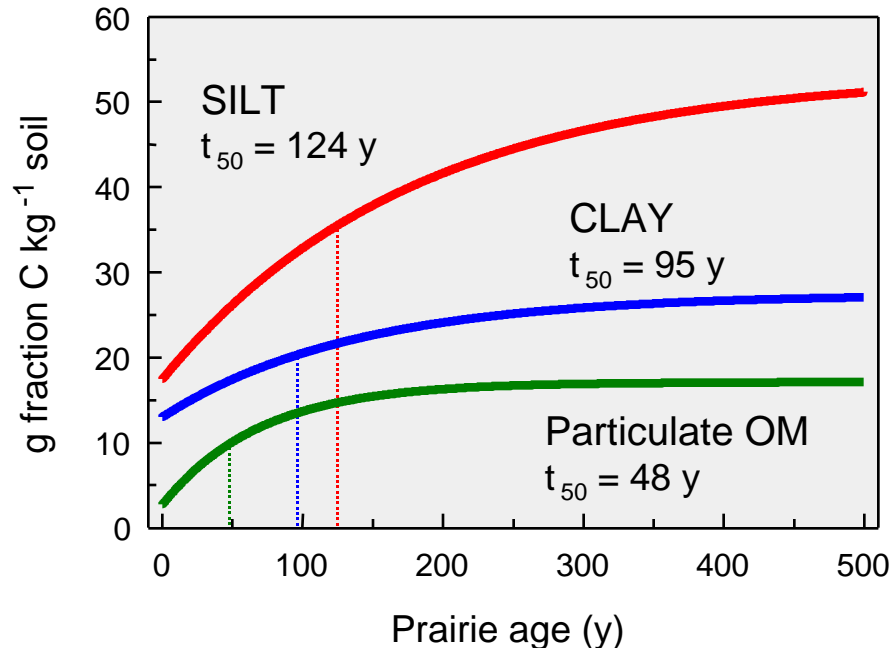
% New (C3-derived) C in fraction

Microaggregate protection
increases the longevity of
silt- and clay-associated C

retained in fraction
% Old (C4-derived)



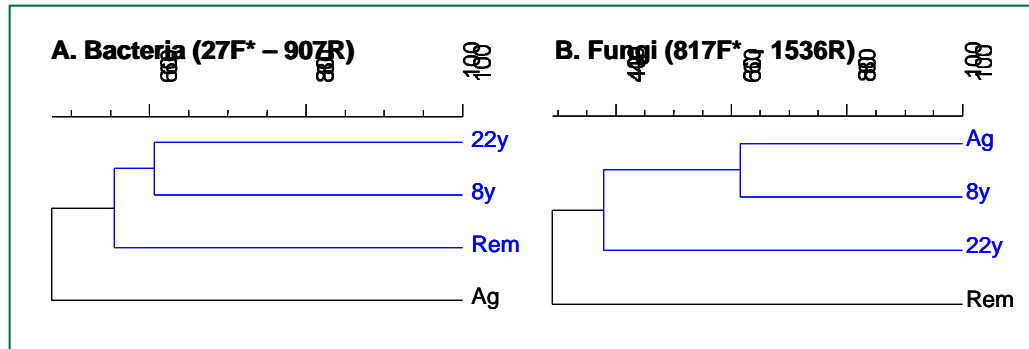
Rates of C accrual vary with particle size



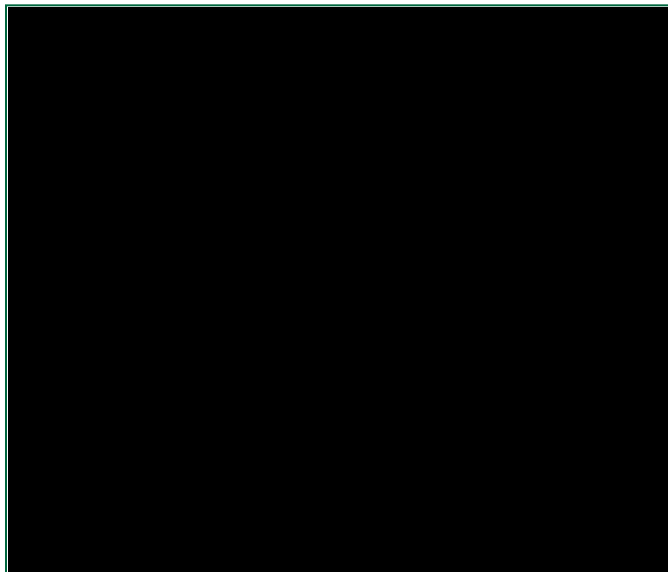
- ⇒ Particulate OM reaches equilibrium first
- ⇒ Largest increases in silt-sized fraction

- ⇒ ~50% of silt-associated C is chemically resistant across the chronosequence
- ⇒ Mineral-associated C has potential for entering longer lived pools

Plant inputs, quality, and manipulations associated with microbial changes



DNA fingerprinting shows bacterial community structures recover faster than fungal communities

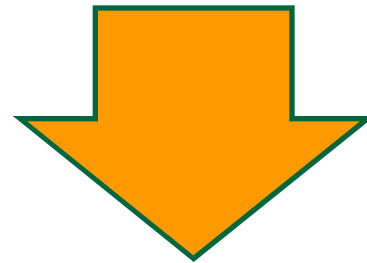


PLFA analyses indicate:

- ⇒ Changes in relative abundance of microbial functional groups are driven by plant inputs (amounts and quality) and related to changes in SOM and bulk density
- ⇒ Fungal:bacterial ratios directly related to plant inputs
- ⇒ Mycorrhizal fungi account for most of the increased fungal abundance

Increases in soil fungal:bacterial ratios
and microbial diversity could increase
the longevity of stored C

- ⇒ Fungi use carbon more efficiently than bacteria
(more C goes to biomass and less to respiration)
- ⇒ Fungal cell walls are more difficult to decompose
(e.g., chitin, melanin)

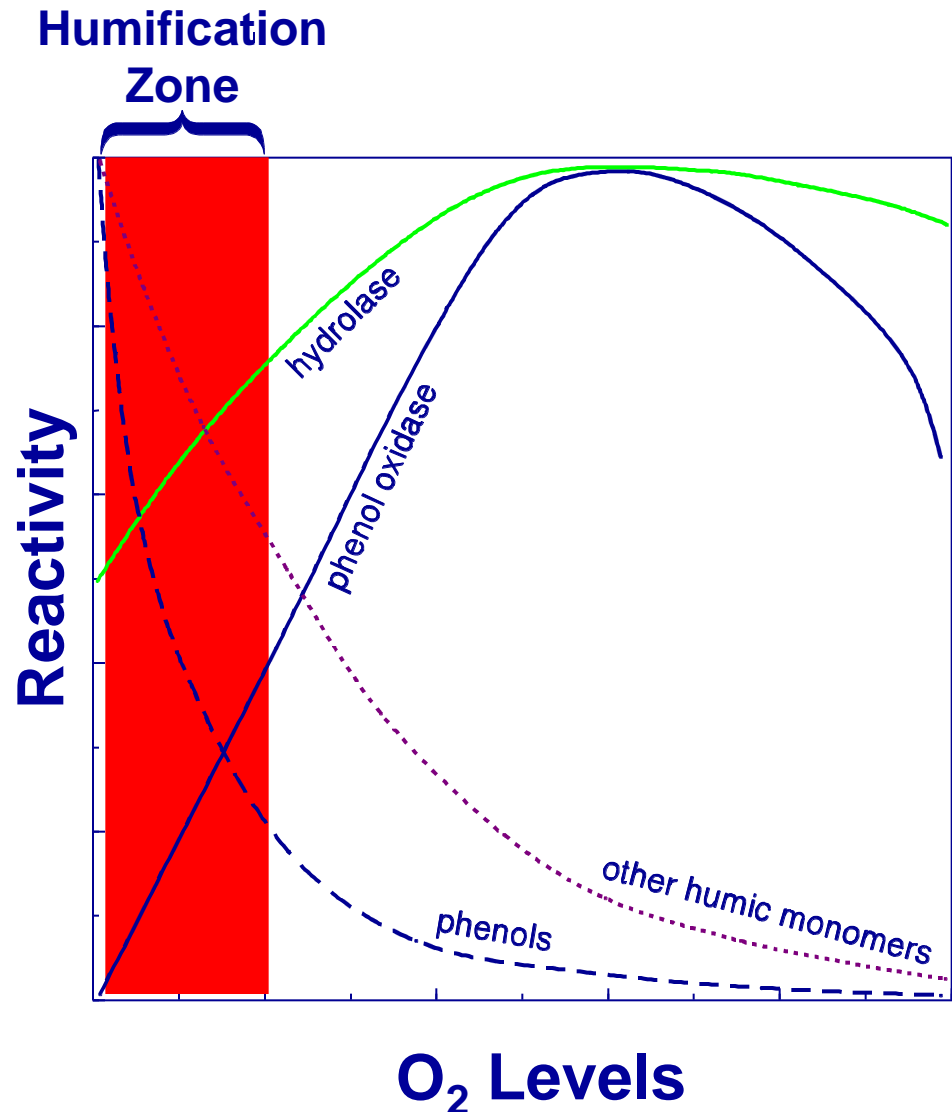


Managing plant communities or cultivars
could effect micro-scale changes that may
enhance sequestration

Can we optimize humification?

Sequestration in prairie soils provides clues

- ⇒ Redox conditions
 - Wetting/drying cycles
 - Aggregation and roots density affect microsite conditions
- ⇒ Fe/Mn oxide content
 - Fe/Mn nodules
- ⇒ Enzyme activities
 - Roots with relatively high lignin contents
 - High fungal:bacterial ratios
 - Microaggregate pores may help stabilize enzymes





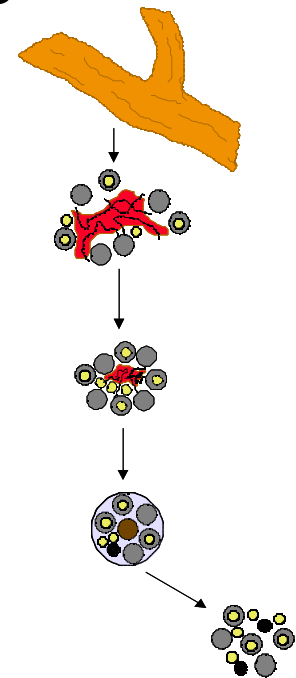
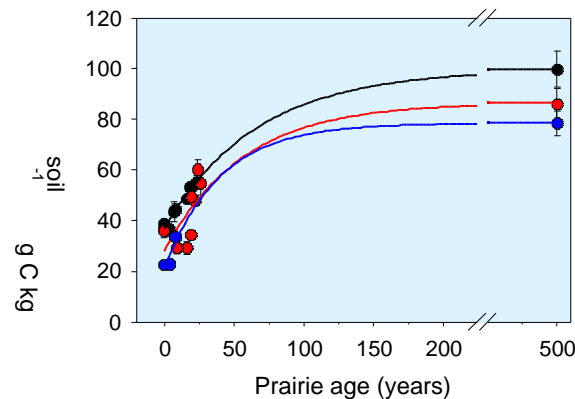
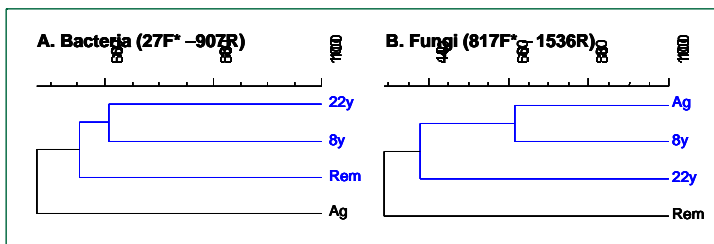
Multi-scale/Multi-disciplinary Research: Significance & Summary

⇒ Quantifying C sequestration rates and potentials

- Model verification and validation
- Contribute to improved spatial and temporal extrapolations

⇒ Providing process-based and mechanistic understanding

- Basis for model improvements
- Design experimental systems to test potential management strategies for enhancing C sequestration





Model Development to Extrapolate Process Scale Results to the Landscape: *Examples from Coshocton and Fermilab*

César Izaurralde

Pacific Northwest National Laboratory

**(with W. Post, ORNL; R. Lal, Y. Hao, P. Puget, Ohio St.
Univ.; L. Owens, USDA-ARS; J. Williams, Texas A&M Univ.;
J. Jastrow, R. Matamala, ANL)**

March 19, 2003

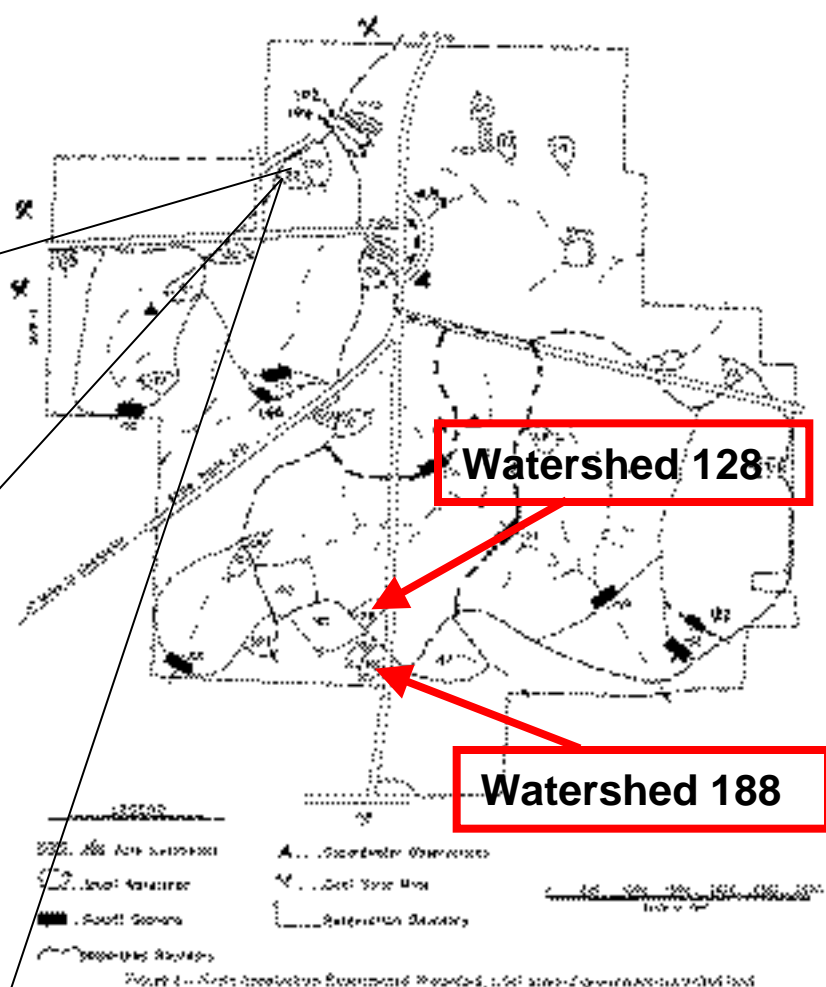


Suitability of the North Appalachian Experimental Watershed (NAEW) for Spatial and Temporal Extrapolation of soil C sequestration

- ⇒ **NAEW (Coshocton, OH) contains several long-term experiments reflecting dominant Midwest U.S. cropping practices**
 - **Corn-soybean rotations**
 - **No till (NT) vs. plow till (PT) corn systems**
- ⇒ **Management history has been kept since 1938**
- ⇒ **Historical measurements of soil carbon, crop production, and soil erosion losses are available**
- ⇒ **Detailed climate and soils information are available for modeling inputs and parameters**

NAEW History and Layout

- ⇒ Entire watershed divided into small bermed sub-catchments with separate treatments
- ⇒ Current rotations established in 1976



CSiTE Work Summarized Existing Information and Initiated Process Studies

- ⇒ **Completed survey of management effects on soil C and N**
- ⇒ **Initiated process studies to examine mechanisms associated with observed soil C differences**
 - **Developed new method of determining soil C loss due to erosion**
 - **Used particle size fractionation and isotopic analysis to examine mechanisms of soil carbon accumulation and fate**
- ⇒ **Conducted simulation modeling studies of soil C dynamics and erosion using data from long-term studies**

Management effects on C and N stocks

Puget et al.

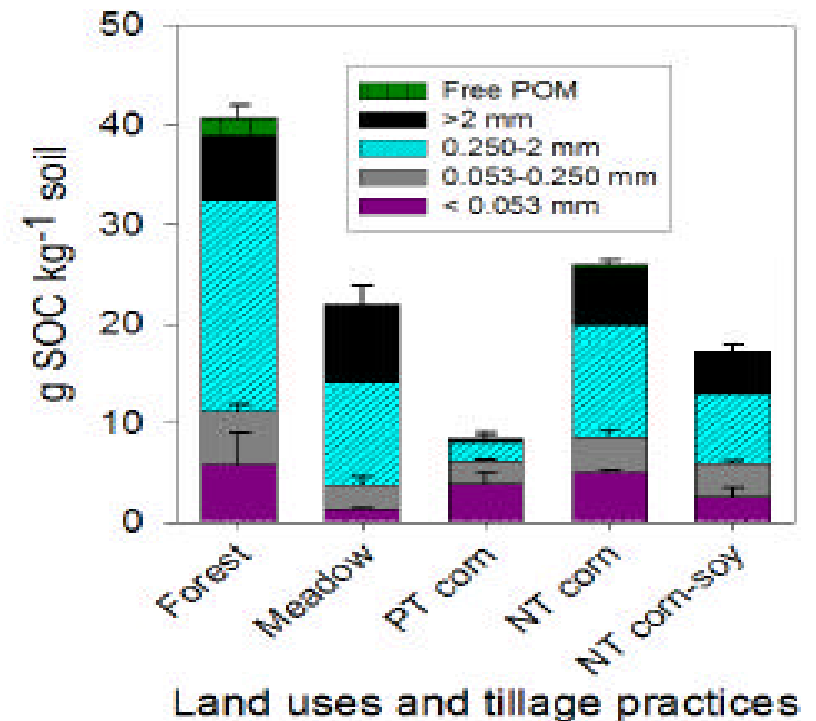
	Soil C (Mg ha ⁻¹)	Soil N (Mg ha ⁻¹)
Old growth forest	65	5.8
Meadow (Hayed field)	49	4.8
Plow till corn	41	3.5
No till corn	52	5.6
No till corn-soybean	47	5.3

- ⇒ Plow till corn soil contained 63% of C in forest soil
- ⇒ No till corn had highest soil C content of all managed systems
- ⇒ Soil N content in no till soils was very similar to that found in forest soils

Carbon and soil aggregates

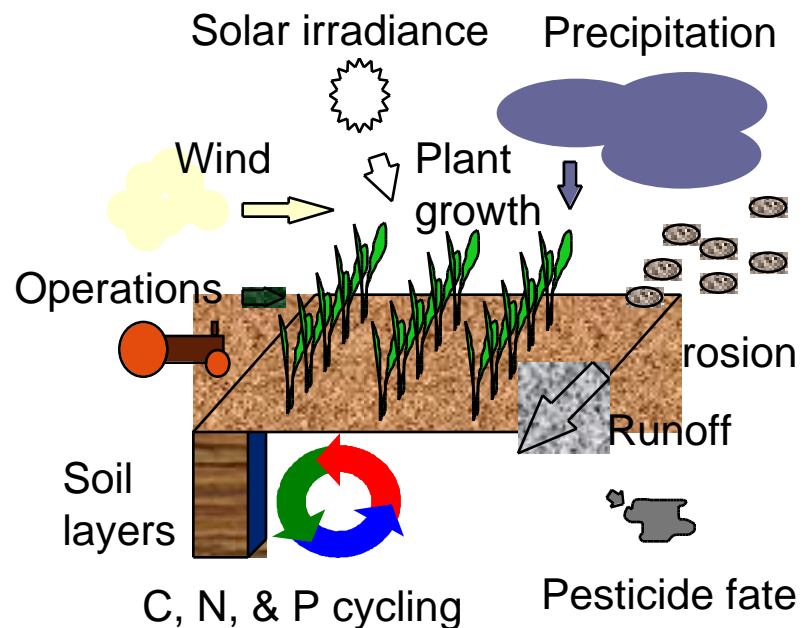
Puget et al.

- ⇒ Carbon distributed differently among soil aggregate fractions
- ⇒ Larger aggregates contained more C than smaller aggregates, except in PT corn
- ⇒ ¹³C analysis revealed that corn residues represented about the C in PT corn while it represented >90% in NT corn



Integrating soil and biological processes at landscape scale through simulation modeling

EPIC Model



Representative EPIC modules

Williams (1995)

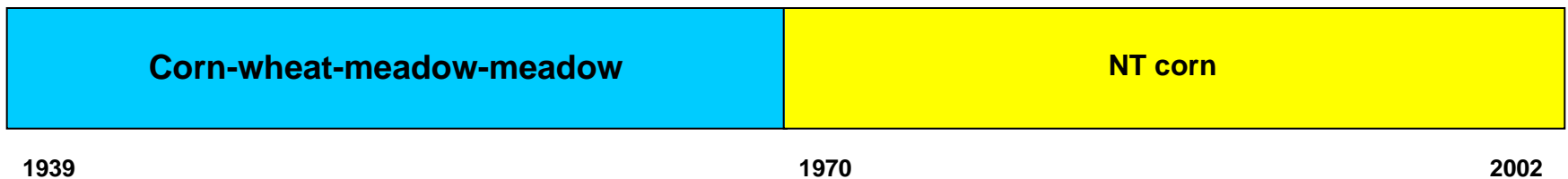
- ⇒ EPIC is a comprehensive model to describe climate-soil-management interactions at point or small watershed scales
- ⇒ EPIC estimates the impacts of management on wind and water erosion
- ⇒ CSiTE investigators recently updated C & N modules in EPIC (Izaurre et al., 2001)
- ⇒ CSiTE data could be used to improve applicability of the model for spatial and temporal extrapolation
- ⇒ Combined with regional databases, this and other models (e.g., Century) can extend observations over conditions not directly measured

Land-use History for Conventionally Tilled (CT or PT) and No Tilled (NT) Watersheds (Puget et al.)

Watershed 128 (W128)



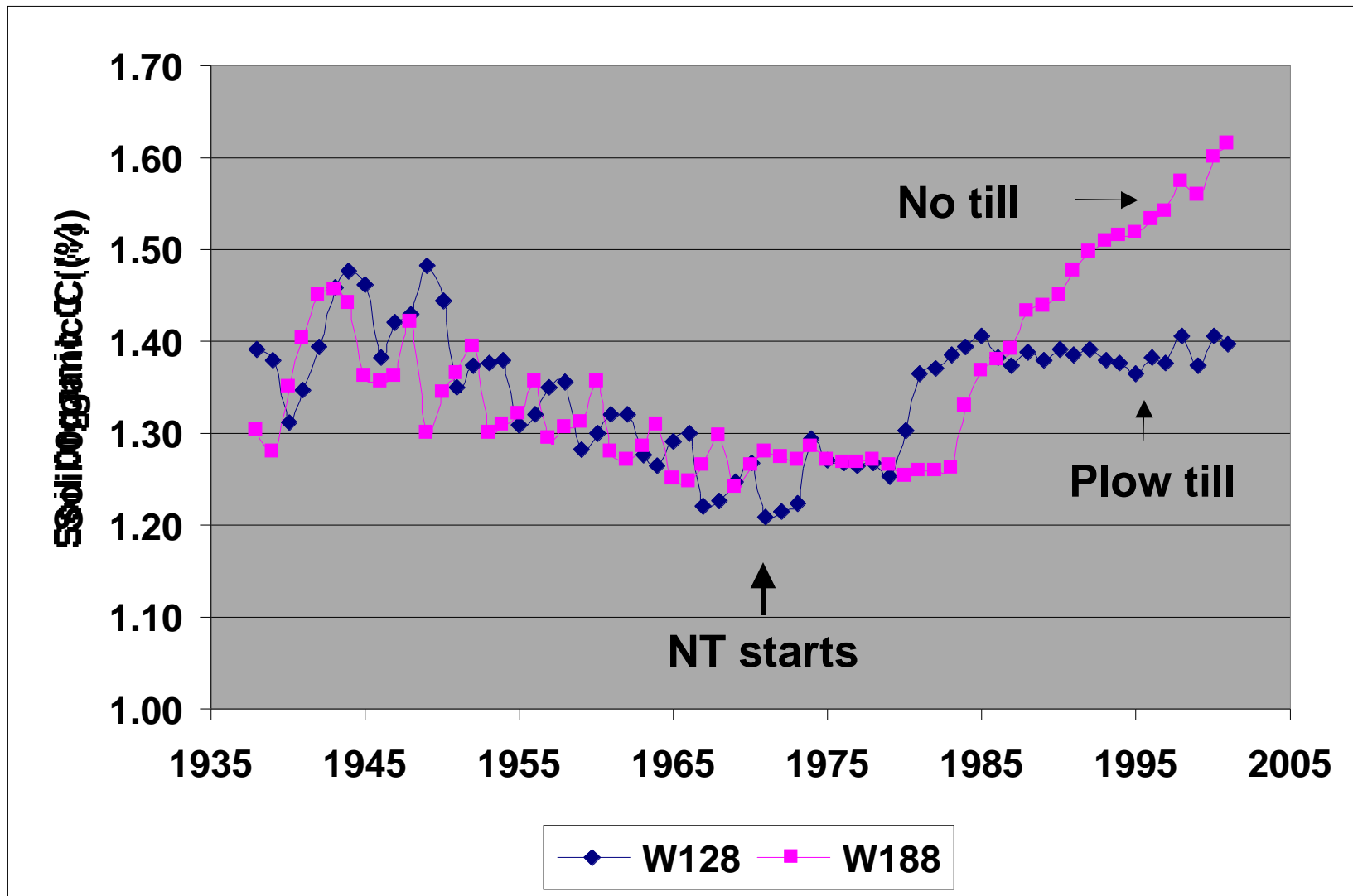
Watershed 188 (W188)



- ⇒ The EPIC model prepared to study management and erosion effects on soil C of W128 and W188
- ⇒ A 63-y weather record was assembled using data from New Providence, OH
- ⇒ Crop modeled included: corn, wheat, timothy, fescue, and alfalfa
- ⇒ Soil layer properties were obtained from Kelley et al. (1975) and L. Owens (pers. comm.)
- ⇒ Two 63-y runs (1939 – 2001) were made with management described above
- ⇒ CO₂ concentration increased from 296 to 370 ppm (25% increase)

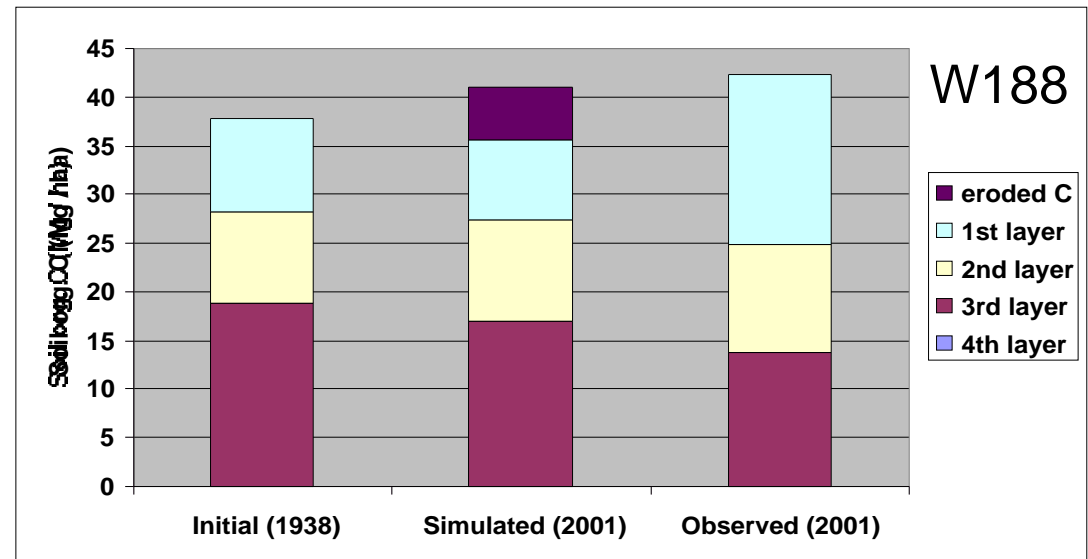
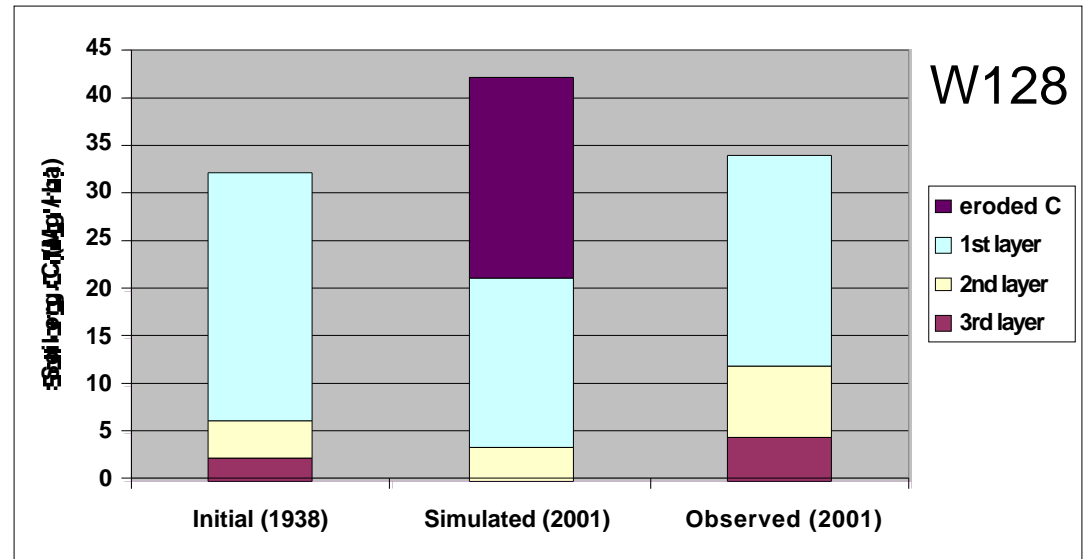
Modeling Results for NAEW

63 year simulation without erosion



Soil C stocks to 20 cm depth in Plow till (W128) and No till (W188) watersheds

- ⇒ Soil erosion altered depth of soil layers
- ⇒ Simulated C stocks were lower than observed values
- ⇒ Eroded C in W188 was _ that of W128



Data source: Puget et al.

A comparison of annual rates of soil C erosion ($\text{Mg C ha}^{-1} \text{ y}^{-1}$) measured or estimated in NAEW watersheds

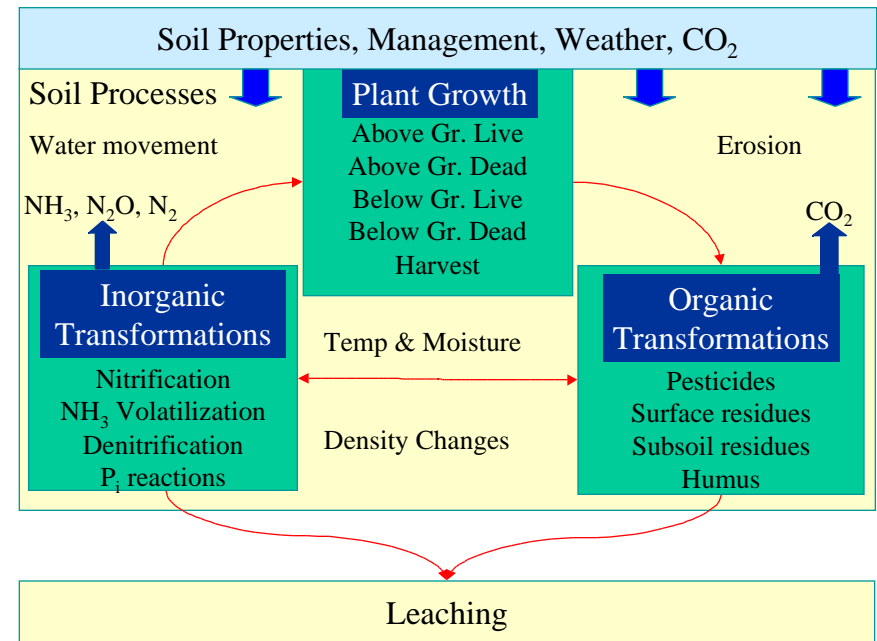
Detail of Coshocton wheel



Source	Period	^{137}Cs	RUSLE	EPIC	Soil sediment collected
Hao et al. (2001)	1951 – 1998	0.041	0.149	-	0.026
This study W128	1939 – 2001	-	-	0.333	-
This study W188	1939 – 2001	-	-	0.084	-

Modeling soil C dynamics in a prairie restoration experiment at Fermilab

- ⇒ The EPIC model was used to study soil C dynamics in prairie restoration experiment
- ⇒ A 25-y weather record was assembled from Aurora, IL
- ⇒ Crop parameters were adapted for modeling big bluestem growth
- ⇒ Soil layer properties for the Drummer soil were obtained from STATSGO database and complemented with site information
- ⇒ A 25-y run (1975 – 1999) simulated the conversion of an agricultural field to a pure stand of big bluestem
- ⇒ N deposition was simulated at a rate of 2.1 mg/L (NADP)



Izaurrealde et al. (2001)

Simulated and observed average above and below ground big bluestem biomass (Mg/ha)



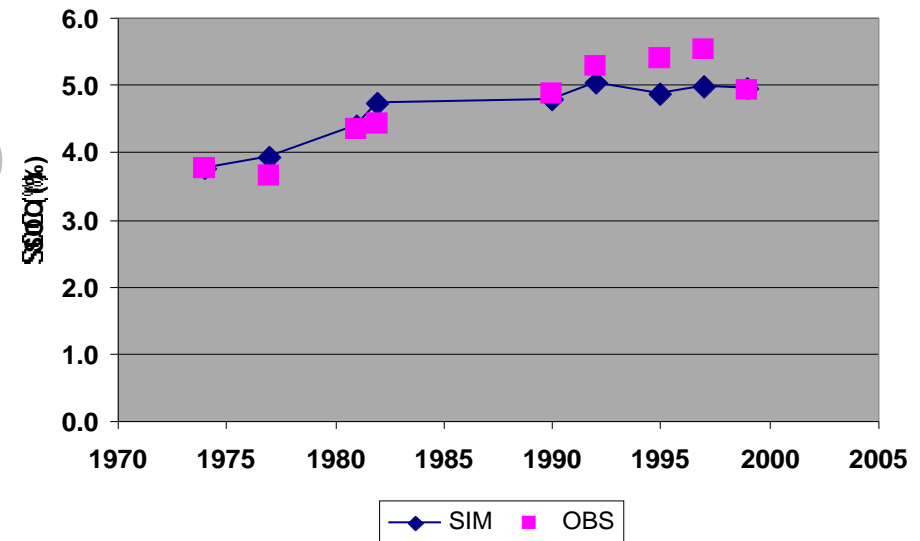
Andropogon gerardii

	Above ground biomass	Roots 0-5 cm	Roots 5-15 cm	Roots 15-25 cm	Root / Shoot ratio
Simulated	8.5	6.9	3.7	1.1	1.38
Observed	8.3	9.0	3.1	1.8	1.67

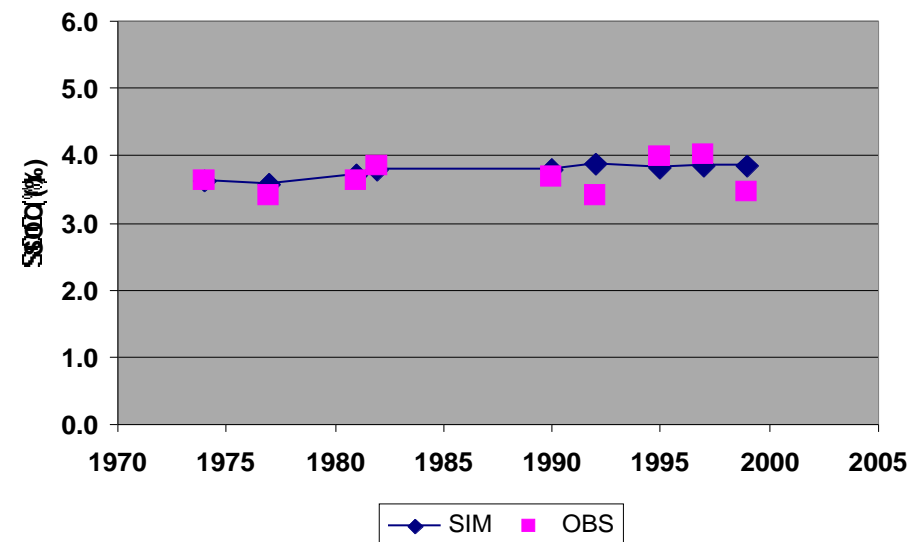
Simulated and observed soil C (%) under big bluestem vegetation

- ⇒ Overall, EPIC captured the soil organic C dynamics observed during 25 years in the Fermilab chronosequence experiment
- ⇒ Most of the observed increase in soil C occurred in the top 5 cm soil depth
- ⇒ The simulated annual rate of soil C accrual to 15 cm depth was lower than the one observed:
 - Simulated: 0.34 Mg/ha
 - Observed: 0.54 Mg/ha
- ⇒ The under prediction of soil C by the model may be related to the under prediction of root and rhizome biomass in the top 5 cm soil depth

0-5 cm depth

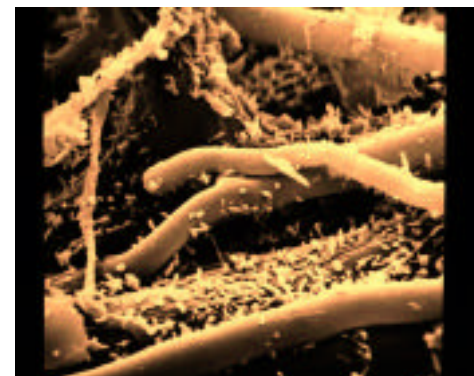


5-15 cm depth



Initial and final soil microbial biomass C (%) in Fermilab chronosequence

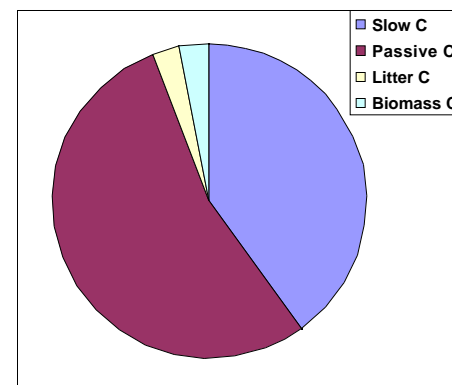
	0-5 cm	5-15 cm	15-25 cm
Initial (1974)	1.0	1.0	1.0
Final (1999) Simulated	3.2	2.7	2.6
Final (1999) Observed	3.1	2.7	2.5



Credit: R. Campbell. 1985. Plant Microbiology. Edward Arnold, London. p. 149.

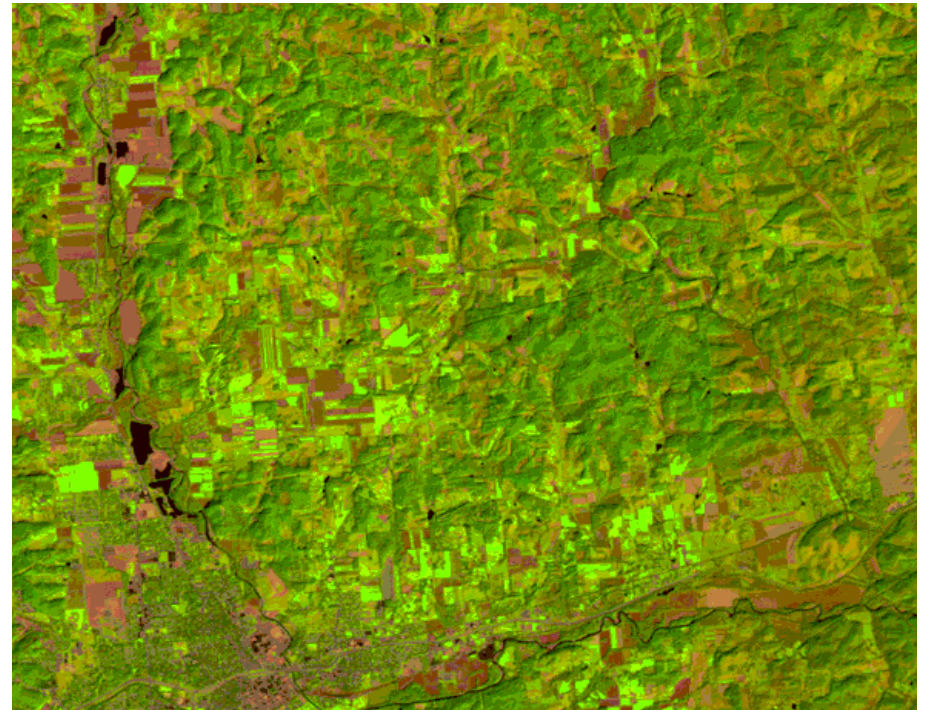
Distribution
of C within
soil C pools

- ⇒ **Passive C represented ~54% of the total**
- ⇒ **Most of the C accrual occurred in the slow C pool**



Using Model Results to Calculate Regional Soil C Sequestration

- ⇒ Data from Coshocton and Fermilab and simulation modeling allow estimating
 - C sequestration potential over time
 - C in eroded sediments
- ⇒ The model can be used to extrapolate to regional edaphic and management conditions
 - Multi-field version of EPIC
- ⇒ Capability to simulate non-CO₂ gases (e.g. N₂O) will be available in near future



**Land use pattern in NAEW region:
Forests, meadows and cropland**



Summary

⇒ Long-term experiments at Coshocton

- Have historical record needed to study temporal and spatial dimensions of soil C dynamics
- Provided opportunity to study processes that control soil C accumulation or loss under traditional and alternative management
- Improved our understanding of the role of erosion in soil C sequestration

⇒ CSiTE investigators

- Enhanced modeling tools to conduct comprehensive evaluations of soil C sequestration
- Conducted extensive tests of model performance using data from Coshocton, Fermilab and other experiments worldwide



Integration for Regional Carbon Sequestration Evaluation

Wilfred M. Post
Oak Ridge National Laboratory
(And CSiTE Team)
March 19, 2003

Need for an Integrated Approach

- ⇒ **Agricultural, silvicultural, and land-use management for C sequestration will be adopted only if:**
 - Amount, capacity, and longevity are known,
 - Net reductions in greenhouse gases occurs,
 - Methods are environmentally beneficial, and
 - Economic aspects are attractive.
- ⇒ **Science methods need development to take discoveries in C sequestration at the plot scale to perform regional scale environmental and economic analyses.**

Integrated Approach to Evaluating Terrestrial C Sequestration

CSiTE is developing an approach that involves:

- ⇒ **Identification of promising technologies**
- ⇒ **Understanding basic mechanisms**
- ⇒ **Performance of sensitivity analysis**
- ⇒ **Inclusion of full C and GHG accounting**
- ⇒ **Evaluation of environmental effects**
- ⇒ **Performance of economic analysis**

1. Identification of Promising Technologies

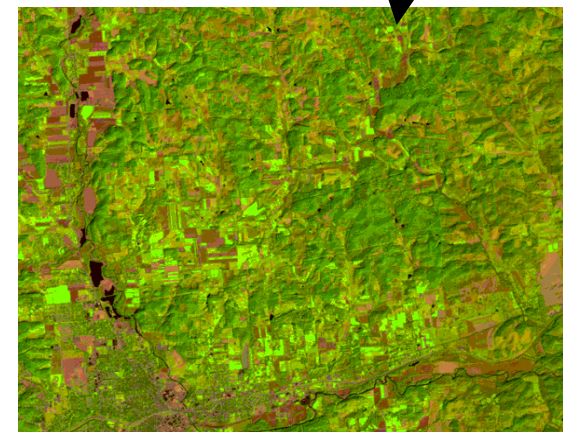
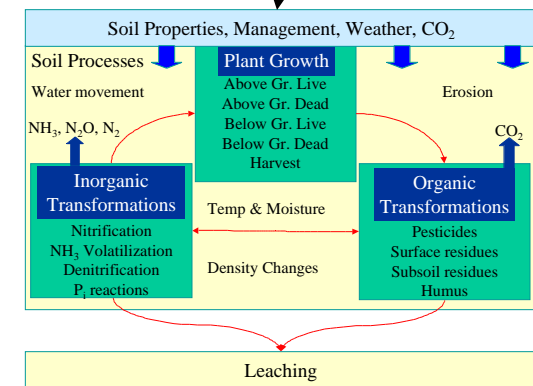
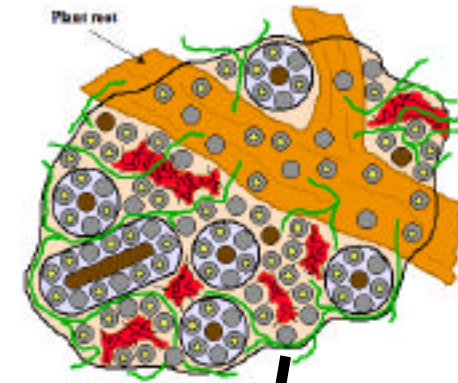
- ⇒ Analysis of sequestration in existing practices.
- ⇒ Identification and testing of novel manipulations.

2. Understand Controls and Basic Mechanisms

- ⇒ Edaphic, biological, and environmental conditions.
- ⇒ Physical protection, biochemical recalcitrance, chemical protection.

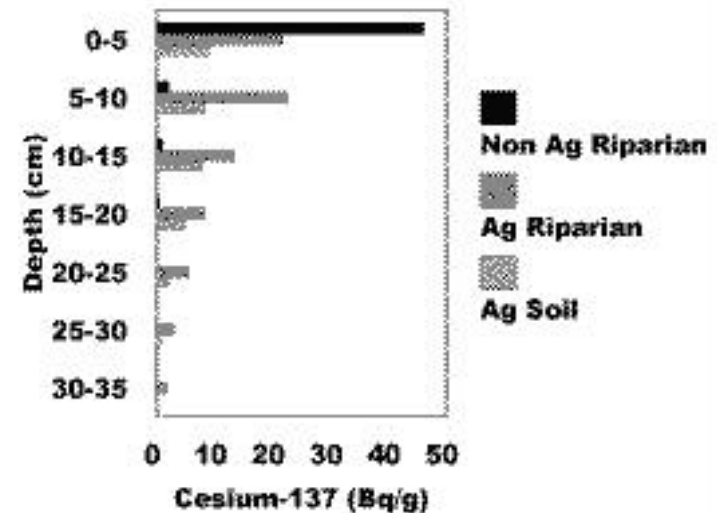
3. Perform Sensitivity Analysis for Spatial and Temporal Extrapolation

- ⇒ Models generalize experimental results.
- ⇒ Use models and GIS data calculate sequestration.



4. Inclusion of Full C and GHG Accounting

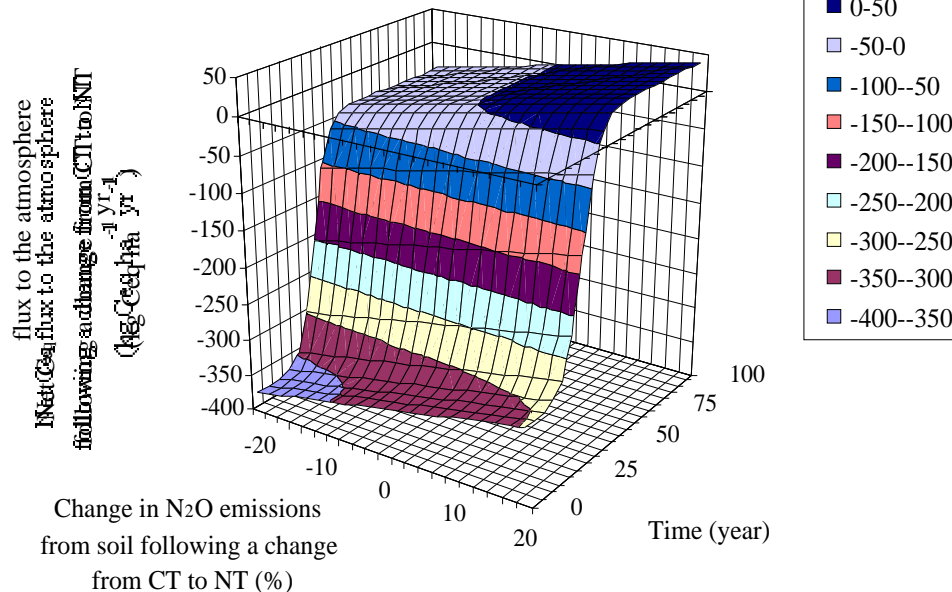
⇒ Include net GHG emissions for all components of management.



5. Evaluation of Environmental Effects

⇒ Erosion control,
water quality

⇒ Biodiversity



6. Perform Economic Analyses

⇒ For a management practice to be adopted it must be:

- Cost effective
- Involve tolerable amounts of risk
- Have a market (economic) method or a fair governmental (social) method of implementation

⇒ Economic models require a **cost per ton** calculation

⇒ Cost per ton should include:

- Net cost of practice, amount of GHG offset
- Producer development cost, adoption inducement cost
- Market transaction costs, governmental costs
- Discounts
- Value of co-benefits

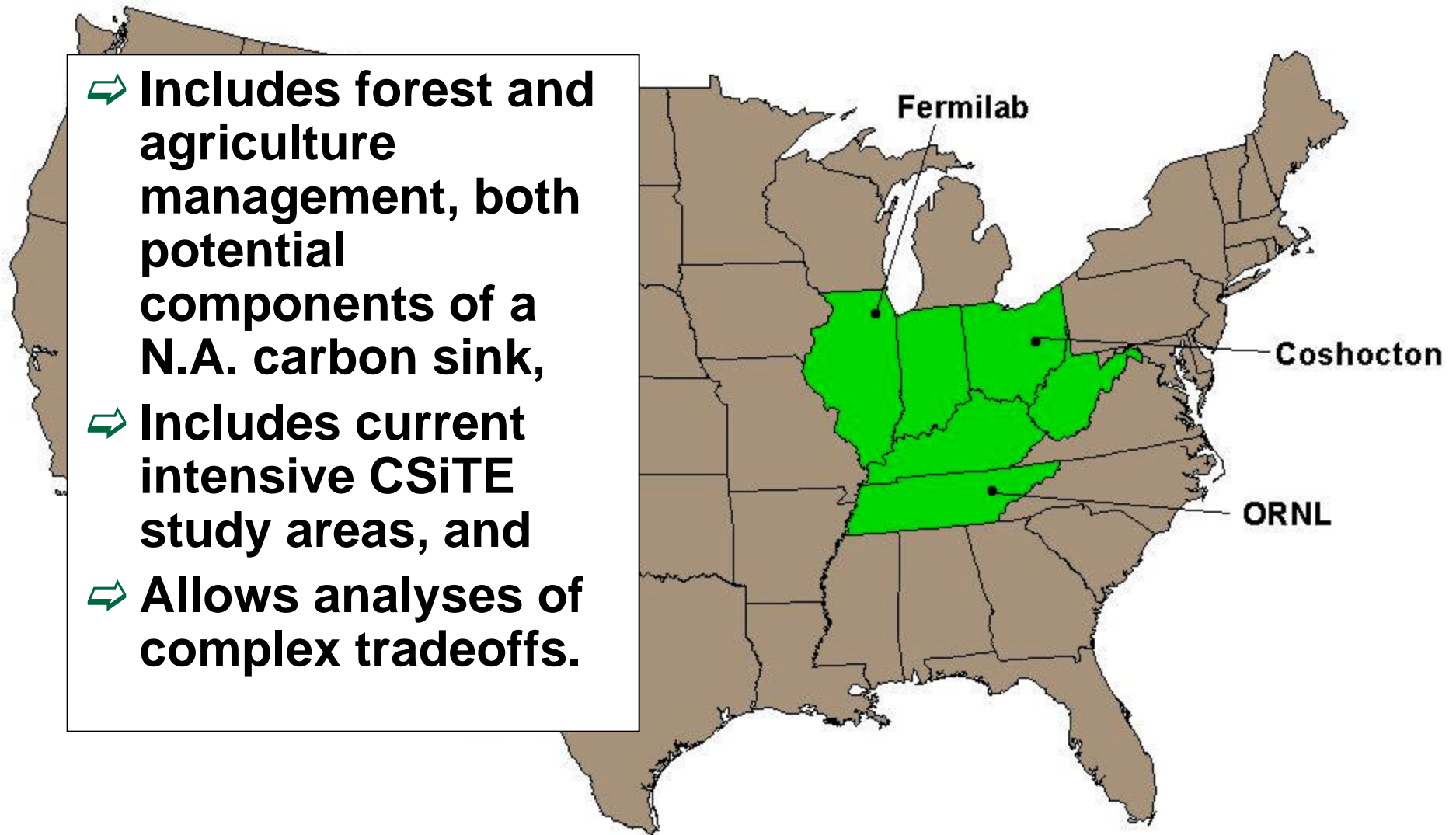
$$\text{Cost per ton} = \frac{\text{net cost of practice}}{\text{amount of GHG offset}}$$

$$\text{Private cost per ton} = \frac{(\text{PDC} + \text{PAIC} + \text{MTC} - \text{GC})}{\text{GHGO} * (1 - \text{DISC})}$$

$$\text{Social cost per ton} = \frac{(\text{PDC} + \text{PAIC} + \text{MTC} + \delta * \text{GC} - \text{CB})}{\text{GHGO} * (1 - \text{DISC})}$$

CSiTE Integration Activity: Potential Region

- ⇒ Includes forest and agriculture management, both potential components of a N.A. carbon sink,
- ⇒ Includes current intensive CSiTE study areas, and
- ⇒ Allows analyses of complex tradeoffs.





Regional Integration Activity Summary

- ⇒ **Integrated approach allows full evaluation of merits of a proposed C sequestration practice.**
- ⇒ **Series of steps for evaluating C sequestration enhancement method involve:**
 - **Identify promising techniques**
 - **Understand controls and basic mechanisms**
 - **Perform sensitivity analysis**
 - **Include full C and greenhouse gas accounting**
 - **Evaluate environmental impacts**
 - **Perform economic analyses**
- ⇒ **CSiTE is completing a concept paper and developing an approach to analyze a diverse region of the U.S.**
- ⇒ **Integrated evaluation framework can**
 - **Reveal gaps in our data and knowledge base.**
 - **Guide evaluation of proposed new soil C sequestration methodologies.**



Summary

F. Blaine Metting, Pacific NW National Laboratory
and **CSiTE Team**

CSiTE Mission: Fundamental science supporting approaches for enhanced C sequestration in terrestrial ecosystems

CSiTE Goal: Establish the scientific basis for enhancing C capture and long-term terrestrial sequestration
via Discovery and characterization of critical pathways and mechanisms to create larger, longer-lasting C pools

Accomplishments to date:

- New R&D tools – Experimental & modeling approaches
- Insights – Biological & physical controls of C seq., economic & environmental impact potential
- Emerging manipulation concepts

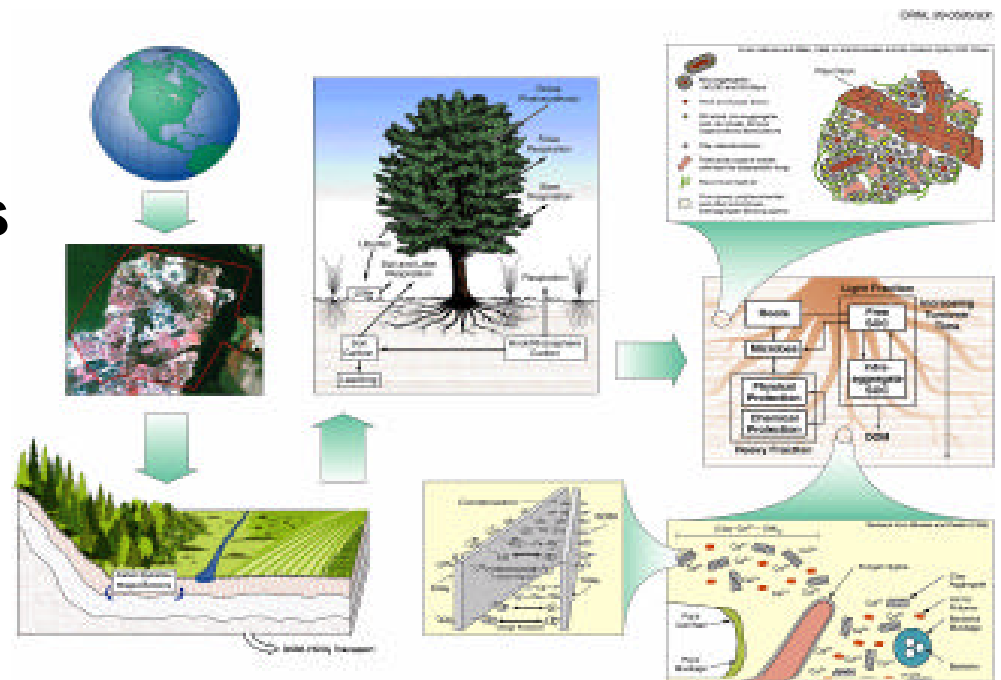
Future CSiTE Directions

⇒ Continue

- Multi-scale/multi-disciplinary research
- Model development & landscape extrapolations

⇒ Explore

- New manipulations
- Regional analyses



Questions ?

